

# How to empower commercial satellite launch supply chain: Insurance, government subsidy or blockchain adoption?

Jichang Dong<sup>a</sup>, Yihan Jing<sup>a,b,c</sup>, Zhou He<sup>a,c,d,\*</sup>, Ciwei Dong<sup>e</sup>

<sup>a</sup>*School of Economics and Management, University of Chinese Academy of Sciences, 3 Zhongguancun Nanyitiao, China*

<sup>b</sup>*Sino-Danish College, University of Chinese Academy of Sciences, 80 Zhongguancun East Road, Beijing 100190, China.*

<sup>c</sup>*Key Laboratory of Big Data Mining and Knowledge Management, Chinese Academy of Sciences, 80 Zhongguancun East Road, Beijing 100190, China.*

<sup>d</sup>*MOE Social Science Laboratory of Digital Economic Forecasts and Policy Simulation at UCAS, 3 Zhongguancun Nanyitiao, China*

<sup>e</sup>*School of Business Administration, Zhongnan University of Economics and Law, Wuhan 430073, China*

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## Abstract

The commercial launch industry is booming with possible launch failures, which can cause enormous loss for both vehicle manufacturer and satellite operator. To hedge such risks and reduce potential costs, they often buy launch insurance from financial companies, and/or seek possible subsidy from government-backed schemes. Recently, the innovative blockchain technology has been adopted by satellite launch supply chains to enhance data sharing, improve workflow efficiency, and thus reduce launch risks. However, very little research has been done on how these players interact, make decisions, and how the satellite launch supply chain (SLSC) can be empowered by insurance, government subsidy or blockchain adoption. In this paper, we propose several Stackelberg games to examine the SLSC cases with launch insurance (Model I), with insurance & government subsidies (Model IG), with blockchain-embedded insurance (Model B), and with blockchain-embedded insurance & government subsidies (Model BG). We investigate the optimal launch price, retail price, and the effort (for improving launch success probability) expressions by deriving models. Furthermore, we explore the conditions for optimal allocation of government subsidies and the cost thresholds for adopting blockchain technology by analyzing the equilibrium outcomes. We find that if the government wants to form a virtuous circle and optimize the allocation of funds, it should subsidize satellite operators that use cost-effective vehicles for launch activities rather than providing unconditional subsidies. In addition, we also find that

the subsidy does not benefit consumers, but blockchain can. Once the blockchain technology is adopted, contract prices go up, the vehicle manufacturer exerts more effort, and the premium rate always is lower as the launch missions become more efficient and believable. Besides, the adoption of blockchain technology can also improve the benefits from government subsidies. Moreover, when the satellite operator chooses an inexpensive launch vehicle, the cost-advantage blockchain-embedded platform benefits all participants. Finally, coupling these findings, we further discuss the managerial implications for the commercial space launch market.

*Keywords:* Satellite launch, insurance, government subsidy, blockchain, commercial launch supply chain

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\*Corresponding author. Tel.: +86 10 88250000; fax: +86 10 88250000.

*Email addresses:* jcdong1c@ucas.ac.cn (Jichang Dong), jingyihan18@mails.ucas.ac.cn (Yihan Jing), hezhou@ucas.ac.cn (Zhou He), dongciwei@zuel.edu.cn (Ciwei Dong)

# 1. Introduction

## 1.1. Background

Man-made satellites can collect extensive and valuable data which can be used in archaeology, cartography, environmental monitoring, meteorology, and reconnaissance applications. Space is no longer confined to government and military agencies like NASA, but open to private companies since 1980s, thanks to the changes of space laws and regulatory regime (OECD, 2014). On Dec.3th 2013, the SES-8 satellite was successfully delivered by a Falcon 9 launch vehicle made by SpaceX, a private company founded in 2002 shaking up the competitive satellite launch industry by offering lower cost launches than their competitors (Tariq, 2013). This successful launch significantly promotes the global space industry, the total revenue of which reaches \$386 billion by 2021, according to the Satellite Industry Association (Space & Technology, 2022). The commercial satellite industry put a record 1,713 commercial satellites into orbit for the fourth consecutive year, an increase of more than 40% compared to 2020.

Behind such vigorous development, the launch failure risk can not ignored by the companies in satellite launch supply chain (SLSC). Once the launch fails, the loss for both vehicle manufacturer and satellite operator is enormous. To hedge this risk, there are three solutions in practice.

First, space insurance emerged. Insurance companies like *Global Aerospace* have been providing different space insurance services, which can be roughly divided into four types according to satellite project phases: pre-launch insurance<sup>1</sup>, launch insurance<sup>2</sup>, in-orbit insurance<sup>3</sup>, and launch plus life insurance<sup>4</sup>. Among them, the launch insurance is most popular because the launch phase is the riskiest activity and the damage is often catastrophic (Suchodolski, 2018; Gould & Linden, 2000; Kunstadter, 2020).

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<sup>1</sup>Pre-launch insurance covers damage to a satellite or launch vehicle during the construction, transportation, and processing phases prior to launch.

<sup>2</sup>Launch insurance covers losses of a satellite occurring during the launch phase of a project. It insures against complete launch failures as well as the failure of a launch vehicle to place a satellite in the proper orbit.

<sup>3</sup>In-orbit policies insure satellites for in-orbit technical problems and damages once a satellite has been placed by a launch vehicle in its proper orbit.

<sup>4</sup>Third-party liability and government property insurances protect launch service providers and their customers in the event of public injury or government property damage, respectively, caused by launch or mission failure.

Second, the government subsidized. Since the commercial industry promotes the development of high technologies, some governments have introduced policies to subsidize the SLSC. For example, the *Beijing Bureau of Economy and Information Technology* subsidized commercial space enterprises that engage in the production and manufacture of vehicles and satellites, and encouraged them to establish headquarters, sales and operation in Beijing. In addition, the United States not only provided subsidy for launch liability insurance but also awarded the commercial companies directly.

Third, new technology helped. Blockchain, a disruptive technology that facilitates data sharing and trust building, has been adopted by the SLSC companies, such as *SpaceChain*, *IBM* and *Cloud Constellation Corporation*. It is used to share the critical data (e.g., contracts, test results) among trusted parties to make the workflow (e.g., approvals, auditing) more efficient and visible, so that the launch failure risk can be reduced as much as possible (Zheng et al., 2021).

Each solution above introduces new entity (insurance company, government, and blockchain service provider) with different interest into the SLSC. Hence, both the private companies and government are keen to understand the impacts of different solutions on SLSC performance.

## 1.2. Research questions and key findings

This paper aims to study the following research questions (RQ):

RQ1. How to analytically model the interactions among key entities in SLSC, namely vehicle manufacturer (VM), satellite operator (SO) and insurance company (IC)? What is the optimal decision for each entity?

RQ2. How to analyze the impact of government subsidy on the optimal decisions in SLSC?

RQ3. Is blockchain worth adopting to the SLSC? How to understand its impacts on the optimal decisions?

To investigate RQ1, we propose a benchmark model with three entities, called Model I. This model is extended as Model IG to study RQ2 by considering government subsidy. Next, the blockchain technology is introduced into both models as Model B and BG. Comparing the optimal decisions in these four models, we obtain the following results:

(1) Government subsidies can be used to incentivize SO to pay higher launch prices, so that the

VM have the motivation to increase the probability of successful launches, and the overall social welfare (total profit of all players) also increases.

(2) The impacts caused by blockchain technology and government subsidy are similar; the difference is threefold: for SO, blockchain adoption (if the cost is low) increases its data retail price and profit; for VM, its profit depends on the cost of blockchain adoption and vehicle manufacturing; for satellite data customer, its surplus increases.

(3) @@@ try to add another finding/result. No insurance-related results?

@@@carefully enumerate your contributions

The rest of this paper is organized as follows. Section 2 reviews four related research streams. Section 3 establishes the benchmark case with launch insurance (Model I), and introduces government subsidies into an extended case (Model IG). Section 4 examines the impact of blockchain adoption in the SLSC under two scenarios, one with launch insurance (Model B) and one with government-subsidized launch insurance (Model GB). Section 5 relaxes some assumptions to generate new findings. Section 6 concludes this paper and suggests potential topics for future research.

## **2. Literature review**

Our paper is closely related to four research streams: supply chain insurance, space supply chain management, blockchain, and government subsidies.

### *2.1. Supply chain insurance*

Supply chain insurance is a sub-stream of supply chain finance which is extensively studied in today's FinTech era (Zhao & Huchzermeier, 2015; Xu et al., 2018b; Wang et al., 2021a). At an affordable expense, supply chain insurance hedges against the risks caused by internal (e.g., the interruption of funds, and the disruption of logistic) or external (e.g., extreme weather, COVID-19 pandemic) factors (Sodhi et al., 2012; Heckmann et al., 2015).

According to the type of risks @@@ (what kind of types?), the literature on supply chain insurance can be divided into two categories. (1) Combining insurance contracts with supply chain contracts. For example, Lin et al. (2010) compared insurance contract with revenue sharing

contract according to different agents' risk aversion based on the news-vendor model. Besides, Wang et al. (2021b) also discussed which contract is better for supply chain partners between the advanced payment contract, penalty contract, and time insurance contract in the express delivery supply chain. (2) Trade-off between costly commercial insurance and substantial economic losses. For example, Lodree Jr & Taskin (2008) designed an insurance policy framework to quantify the risks and benefits. Yu et al. (2021) considered the interrupt probability of the supply chain, and illustrate that business interruption insurance increases the profit of each participant. Brusset & Bertrand (2018) constructed a weather index, so that entrepreneurial risk can be transferred to other risk-takers through insurance or options contracts.

## *2.2. Space supply chain management*

Space supply chain management can be viewed as a part of space operations. In the early stage, this research stream generally focused on space logistics, e.g., developing an integrated space supply chain management framework (MIT). Taylor et al. (2006) aimed to optimize delivery operation @@@ use what kind of method? According to the research goal, the literature on space supply chain management can also be divided into two categories. (1) Optimizing the operating system to improve the efficiency. Galluzzi et al. (2006) regarded supply chain management as a critical piece of framework in the aerospace industry, and they elaborated the pattern operation in this area. Taylor et al. (2006) also designed and evaluated the operating system in the space supply chain, but they primarily engaged in optimizing delivery operation, which sustains the exploration initiative. Moreover, Gralla et al. (2006) gave a comprehensive model and simulation of the supply chain management implemented in the aerospace industry, which is low-volume and schedule-driven compared to the high-volume and market demand-driven SCM in the commercial sector.

(2) analyzing the business problem in supply chain management. The research on this topic is relatively few. Wooten & Tang (2018) examined the space industry's operation management, which involves manufacturing operations, supply chain management, and sustainable operations. Besides, they also outlined the challenges and essential questions related to stakeholders. Raghunath & Kang (2021) discussed the challenges that commercial space operation faces from a busi-

ness perspective. Furthermore, Guo et al. (2021) comprehensively analyzed the global aerospace industry's current situation and future development from the upstream supply chain, midstream production chain, and downstream application chain. In addition, Donelli et al. (2021) considered the profitability and efficiency during the aircraft manufacturing and supply chain. The paper proposed a model-based approach to optimal the multiple-choice. Furthermore, Dewicki et al. also based on operational management analyze the business model in commercial space.

As review literature, most papers target SCM in space give the mathematical model from optimizing logistics, even the system flow. While our paper builds models from the business angle, we concentrate on the game theory between participants during the launch activity.

### *2.3. Blockchain technology support supply chain management*

As a “trust ledger”, blockchain has overwhelming advantage of data storage such as openness, transparency, tampering, and traceability, which make it possible to manipulate higher quality data (Choi, 2019), improving the supply chain efficiency and so on (Chod et al., 2020). According to its characters, Queiroz et al. (2019); Wang et al. (2019); Babich & Hilary (2020); Li et al. (2022) gave the review of this topic.

Besides, more and more scholars have begun to study the application of blockchain in the supply chain. (1) Inside the supply chain, (i) in upriver, blockchain technology facilitates the flow of raw materials from the suppliers (Naydenova, 2017; Nash, 2016); (ii) in the midstream, it promotes the exchange of manufacture information and design smart contracts between participants in the supply chain upstream and downstream and achieve coordination eventually (Moise & Chopping, 2018; Hilary, 2022; Chod et al., 2020; Korpela et al., 2017; Wang et al., 2021c). (2) Outside the supply chain, (i) face the third party, it provides an innovative way for the capital constraint companies to finance (Choi, 2020; Choi & Ouyang, 2021); (ii) face the market, it helps products to fight counterfeits, earn trust of customers and win company reputation in the market (Pun et al., 2021; Shen et al., 2021; Fan et al., 2020).

Regarding our topic, this article mainly refers to articles on the application of blockchain in the space supply chain. Adhikari & Davis (2020) gave a clearly analysis on the implementation of blockchain in the area of space cybersecurity framework against global positioning system spoof-

ing. Zheng et al. (2021) studied a three-tier space supply chain under the decision-making problem and investigated how blockchain technology optimizes decisions based on information sharing. Moreover, Hyland-Wood et al. (2020) examined three potential blockchain properties applied in space: real-time communication during the interplanetary space operating and operations realm of the solar system. However, different from them, this article's focal point is on launching a service supply chain supported by fintech (blockchain-embedded insurance) to facilitate launching risks and contract pricing.

#### *2.4. Government subsidies*

Government interventions in supply chain management include legislation (Gouda et al., 2016; Zhang & Zhang, 2018), penalties (Xiao & Xu, 2018; Luo, 2020), subsidies (Guo et al., 2019; Xiao et al., 2020; Jung & Feng, 2020) and taxes (Xu et al., 2018a; Chen et al., 2020). The stream of research closest to our work is exploring the adoption of government subsidies to promote industry growth or to support firms through difficult times.

In order to improve the social welfare and the manufacturers' profits, different types of subsidy programs has been launched by governments, such as subsidies to consumers, manufacturers, or both Yu et al. (2018). The authors of this article reveal the influencing factors that determine the optimal structure of government subsidy programs. They find that governments can develop subsidy programs involving multiple competing manufacturers to improve consumer welfare. However, the government subsidy system is not always effective. Hsu et al. (2019) find that the quality subsidy offered to the farmers quality subsidies provided to farmers may reduce not only the quality of dairy products, but also the profitability of companies. Berenguer et al. (2017) analyze the effectiveness of subsidies on a for-profit or a not-for profit firm in inducing consumption. Their study shows that the incentive to a not-for-profit counterpart is more stronger than to a for-profit firm to encourage consumption. Besides, Bai et al. (2021) investigate the design of trade-in subsidy programs by capturing the essence of the interaction between the government, the manufacturer, and consumers. They find that compared with a fixed-amount subsidy, a shared subsidy program in which government subsidies are proportional to manufacturer rebates is more effective in stimulating consumers to trade-in.



In the same vein as the above literature, we also explore the effectiveness of government subsidies in supply chain operations. However, the difference is that we focus on the commercial space supply chain to explore how subsidy systems can be implemented to leverage its value.

### 2.5. Contributions of this paper

Similar to these researches, our paper also adopts the insurance contract to hedge the interrupt risk while the focal point is in the space launch supply chain, which is remarkable for technical complexity, high quality & reliability requirements, and colossal failure losses.

Supply chain insurance with government subsidies and blockchain technology adoption are essential topics in space launch operation management. Based on the real-world observation, we introduce a three-stage Stackelberg game model to explore the value of government insurance subsidies. Besides, motivated by the practice of blockchain application such as IBM and Cloud Constellation Corporation are working together to build a blockchain-based platform in the space launch supply chain, this paper theoretically investigates the blockchain-embedded insurance model operations. The insights not only contribute to the literature in operation management but also advance the industrial knowledge regarding blockchain launch platforms.

## 3. Benchmark case

Consider a make-to-order supply chain consisting of one vehicle manufacturer (VM, he), one satellite operator (SO, she) and an insurance company (IC, it). As shown in Figure 1, to launch the satellite successfully, the SO usually conducts a series analyses to choose the vehicle and design the launch service contract with launch price  $l$  and prepay ratio  $\alpha$ . Once the satellite is on-track, the SO will pay VM last part  $(1 - \alpha)p$  and she will obtain income from sailing satellite data. Without loss generality, consumers possess a stochastic valuation  $u$  towards the satellite data, which follows a distribution  $f(u)$ . Following most literature, we set  $f(u)$  follows a uniform distribution with a range of  $0 - 1$ , denoted by  $U[0, 1]$ . To avoid facing messy mathematics, we normalize the consumer population as 1.

As common in launch activity, our models capture two typical features in the space supply chain. First, the launch activity is risky, which means there is a probability for the satellite op-

erating in its final orbital position. The VM can improve the probability of mission success (aka reliability) by exerting costly efforts (e.g., improving technologies, equipment or processes) (Bailey, 2020; Kunstadter, 2020). Following Tang et al. (2018), we scale the base launch success probability to 0. To increase the probability from 0 to  $e$ , where  $e \in (0, 1)$ , the VM needs to exert effort associated with a disutility (cost of effort)  $ke^2$  with  $k > 0$ . The setting of such a disutility is common in many models.

Notedly, a launch failure is costly to all involved parties. For the SO, she will lost her satellite and the income. For the VM, what he will face is not only the current contract loss but also the damage of his reputation and future business as well as financing. To reflect the VM's additional loss, a penalty denoted by  $\theta$  is adopted into the profit function. Considering the launch risk, it is natural that SO attempts to purchase launch insurance before launching to hedge risks. IC designs the launch insurance according to the analyses of conducting serious technological analyses of satellite and the VM. Once the launch fails, the IC usually pays pro rate compensation. We assume the claim covers  $\beta$  of the whole loss including the cost of satellite and the prepay price.

We summarize the notation used throughout the paper in Table 1.

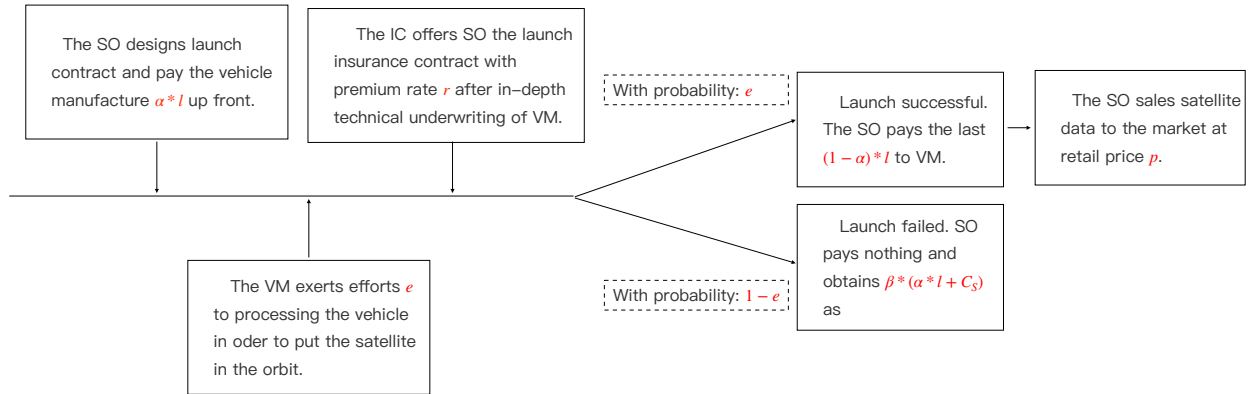


Figure 1: Sequence of events. SO :the satellite operator; VM: the vehicle manufacture; IC: the insurance company.

### 3.1. Model I: Satellite launch supply chain with insurance

Acting as the Stackelberg leader, the SO sets the contract terms and the VM, as the follower, decides whether to accept the contract. Without loss of generality, we focus on the following contract: the SO pays the VM a certain  $\alpha$  of launch price  $l$  upfront when launch services are procured.

Table 1: Notation

Variable	Remark
Model I	Satellite launch supply chain with insurance
Model IG	Satellite launch supply chain with government-subsidized insurance
Model B	Blockchain-embedded satellite launch supply chain with insurance
Model BG	Blockchain-embedded satellite launch supply chain with government-subsidized insurance
$p$	The satellite data retail price
$l$	The launching service price
$\alpha$	The upfront payment ratio
$e$	The “rate of successful launch”, which is the same as “the level of effort the VM exerting” in this paper
$k$	The cost coefficient of effort
$r$	The premium rate
$\beta$	The claim ratio
$g$	The government-subsidized launch insurance premium rates
$c_i$	The cost of vehicle ( $i = V$ ) or satellite ( $i = S$ )
$\theta$	The penalty of a failed launch for VM
$k$	The effort cost factor
$\pi_i$	The profit of vehicle manufacture( $i = V$ ) or satellite operator ( $i = S$ ) or insurance company ( $i = I$ )
$CS$	The consumer surplus
$SW$	The social welfare

<sup>a</sup> Subscripts  $S$ ,  $V$  and  $I$  are the indices of SO, VM and IC respectively.

<sup>b</sup> Superscript  $I$ ,  $IG$ ,  $B$  and  $BG$  to describe function and decisions in model I, model IG, model B and model BG respectively.

(Andrews & Bonnema, 2011; Barschke, 2020) Furthermore, when the launch is successful, the VM then receives the balance of the payment  $(1 - \alpha) * l$  for services or 0 otherwise. Concerning risk, the SO buys the launch insurance with the premium rate  $r$  to compensate the loss if the launch failed. Figure 1 shows the sequence of events corresponding to the game model. Therefore, the market demand and payoff function,  $D^l$  and  $\pi_S^l$ , faces by the SO can be measured as follows:

$$D^l = 1 \int_p^1 f(u) du = 1 - p \quad (1)$$

$$\max_{l,p} \mathbb{E}[\pi_S^l(l, p, e, r)] = epD^l - [\alpha + e(1 - \alpha)]l - r(c_S + \alpha l) + (1 - e)\beta(c_S + \alpha l) - c_S, \quad (2)$$

As shown,  $\pi_S^l$  consists of five parts: (1) the income she can obtain once the satellite works in orbit  $epD^l$ ; (2) the expect launch service price  $[\alpha + e(1 - \alpha)]l$ ; (3) the premium for the launch insurance  $r(c_S + \alpha l)$ ; (4) the compensate she will get once the launch failed  $(1 - e)\beta(c_S + \alpha l)$ . (5) the cost of building the satellite  $c_S$ . Without loss of generality, the satellite income covers its building and launch cost; i.e., the SO sets a contract only when  $pD^l \geq c_S + l$ .

As depicted in Figure 1, the VM accepts a contract with price  $l$  and receives the prepayment  $\alpha * l$  from the SO, then he manufactures the rocket which cost  $c_V$ . If the vehicle launch successfully, he receives the last  $(1 - \alpha) * l$  from the SO. If launching is failed, the VM not only receives no payment but also suffers penalty which monetized as  $\theta$ . Therefore, the VM's objective is to maximize his expected payoff  $\pi_V^l$  as follows:

$$\begin{aligned} \max_e \mathbb{E}[\pi_V^l(l, p, e)] &= [\alpha + e(1 - \alpha)]l - (1 - e)\theta - (ke^2 + c_V), \\ s.t. \pi_V^l &\geq 0 \end{aligned} \quad (3)$$

As shown,  $\pi_V^l$  consists of three parts: (1) the prepaid income and expected gain upon successful launch  $[\alpha + e(1 - \alpha)]l$ , (2) the expected loss of failure penalty in the event of launch failure  $(1 - e)\theta$ , and (3) the cost of effort and vehicle  $ke^2 + c_V$ . The non-negative profit constraint ensures the profitability of launch successfully; otherwise, the VM will quit the cooperation.

### 3.1.1. The VM's effort

We now solve the Stackelberg game as depicted in Figure 1 using backward induction. First, given any launch price  $l$ , by considering the first-order condition of Equation (3), the VM's best response is given as:

$$e(l) = \frac{(1-\alpha)l + \theta}{2k}, \quad (4)$$

$$s.t. \quad 0 < e \leq 1. \quad (5)$$

By substituting Equation (4) into the VM's payoff  $\pi_V^l$  given in Equation (3), it can be obtained that:

$$\pi_V^l = \frac{[(1-\alpha)l + \theta]^2}{4k} + \alpha l - \theta - c_V \quad (6)$$

Hence, considering the VM's participation constraint, i.e.,  $\pi_V^l \geq 0$ , the lowest VM's acceptance (VA) launch price can be written as:

$$l \geq l_{VA} \equiv \frac{2\omega - 2\alpha k - (1-\alpha)\theta}{(1-\alpha)^2}, \quad (7)$$

where  $\omega = \sqrt{k[(1-\alpha)^2 c_V + \alpha^2 k + (1-\alpha)\theta]}$ .

### 3.1.2. The IC's premium rate

Observing the contract price  $l$  selected by the SO, the insurance company can anticipate the VM's effort  $e(l)$  as given in (4). Operating in a competitive market, the insurer sets its rate  $r$  to break-even in expectation. In other words, under the rate  $r$  that it offers, the insurance company's expected payoff,  $r(c_S + \alpha l)$ , equals the amount of coverage,  $(1-e)\beta(c_S + \alpha l)$ . Thus IC's profit function and the premium rate can be written as:

$$\begin{aligned} \pi_i^l &= r(c_S + \alpha l) - (1-e)\beta(c_S + \alpha l), \\ r(l) &= \beta \left[ 1 - \frac{(1-\alpha)l + \theta}{2k} \right]. \end{aligned} \quad (8)$$

### 3.1.3. The SO's optimal price

Anticipating the VM's best response  $e$  given in (4) and the premium rate (8), the SO's payoff given in Equation (2) can be rewritten as:

$$\max_p \mathbb{E}[\pi_S^l(l, p)] = \frac{[pD^l - (1 - \alpha)l] * [(1 - \alpha)l + \theta]}{2k} - \alpha l - c_S, \quad (9)$$

$$l \geq l_{VA}.$$

Checking the Hessian matrix of SO's payoff, we find  $\pi_S^l$  is concave in  $l$  and  $p$  jointly when  $0 < k < \frac{(1-\alpha)(1+4\theta)}{8\alpha}$ . In this paper, we focus on the case when the condition is met. According to the assume, we can get the optimal launch price and optimal retail price for her which are  $l_S = \frac{\phi - 8\theta(1-\alpha)}{8(1-\alpha)^2}$  and  $p^* = \frac{1}{2}$ , where  $\phi = (1 - \alpha)(1 + 4\theta) - 8\alpha k$ . Consider the constraints, the SO aims to select the optimal contract price  $l^* = \max(l_S, l_{VA})$  that maximizes her payoff, given in Equation (9). The optimal contract and corresponding equilibrium outcomes are given in Lemma 3.1.

According to the above derivation, we can also obtain the consumer surplus and social welfare as follows:

$$CS^I = 1 \int_p^1 (u - p)f(u) du = \frac{(D^I)^2}{2}, \quad (10)$$

$$SW^I = \pi_S^I + \pi_V^I + CS^I.$$

By denoting all of the functions, we obtain Lemma 3.1.

**Lemma 3.1.** *The equilibrium outcomes of Model I are shown in Table 2.*

Note that there are two cases in our equilibrium result that  $c_V < H(\alpha)$  and  $c_V \geq H(\alpha)$ , where  $H(\alpha) = \frac{8(1-\alpha)[2\alpha k + \theta(1-\alpha)] + 16\theta^2(1-\alpha)^2 - 192\alpha^2 k^2 - 64\theta k(1-\alpha)(4-\alpha)}{256(1-\alpha)^2 k}$ . This is due to the launch price  $l^* = \max(l_S, l_{VA})$ . In the first case, the optimal launch price  $l_S$  fixed by the SO is higher than  $l_{VA}$ , which means the contract launch price  $l^*$  is  $l_S$  equaling  $c_V < H(\alpha)$ . In the second case, SO's optimal launch price  $l_S$  is lower than  $l_{VA}$ , so she has to fix the contract price  $l^*$  as  $l_{VA}$  to avoid the profit of VM being negative; otherwise the VM will quit the cooperation.

According to the equilibrium outcomes, we now conduct the sensitivity analyses for Model I and summarized the outcomes in Table 3.

Table 2: The equilibrium outcomes in Model I.

	$c_V < H(\alpha)$ (i.e., $l_S > l_{VA}$ )	$c_V \geq H(\alpha)$ (i.e., $l_{VA} \geq l_S$ )
Effort of VM exerting $e^*$	$\frac{\phi}{16(1-\alpha)k}$	$\frac{\omega-\alpha k}{(1-\alpha)k}$
Launch price $l^*$	$l^* = l_S = \frac{\phi-8\theta(1-\alpha)}{8(1-\alpha)^2}$	$l^* = l_{VA} = \frac{2\omega-2\alpha k-(1-\alpha)\theta}{(1-\alpha)^2}$
Retail price $p^*$	$\frac{1}{2}$	$\frac{1}{2}$
Premium rate $r^*$	$\beta(1 - \frac{\phi}{16(1-\alpha)k})$	$\beta \frac{k-\omega}{(1-\alpha)k}$
SO's profit $\pi_S^I$	$\frac{\phi^2}{128(1-\alpha)^2k} + \frac{\alpha\theta}{1-\alpha} - c_S$	$\frac{(\omega-\alpha k)(\phi+8\alpha k-8\omega)}{4(1-\alpha)^2k} + \frac{\alpha\theta}{1-\alpha} - c_S$
VM's profit $\pi_V^I$	$\frac{\phi^2+32\alpha k\phi}{256(1-\alpha)^2k} - \frac{\theta}{1-\alpha} - c_V$	0
Consumer surplus $CS^I$	$\frac{1}{8}$	$\frac{1}{8}$
Social welfare $SW^I$	$\frac{3\phi^2+32\alpha k\phi}{256(1-\alpha)^2k} - \theta - c_S - c_V + \frac{1}{8}$	$\frac{(\omega-\alpha k)(\phi+8\alpha k-8\omega)}{4(1-\alpha)^2k} + \frac{\alpha\theta}{1-\alpha} - c_S + \frac{1}{8}$

To avoid complicated writing, we define  $\phi = (1-\alpha)(1+4\theta) - 8\alpha k$ ,  $\omega = \sqrt{(1-\alpha)^2kc_V + \alpha^2k^2 - (1-\alpha)k\theta}$ .

Firstly, we explore how the cost coefficient of effort  $k$  affects the equilibrium outcomes mentioned above. If the cost coefficient of effort  $k$  increases, (a) no matter what the manufacturing cost of the vehicle  $c_V$  is, (i) the effort exerted by the VM  $e$  and the launch price  $l$  will always decrease; (ii) the premium rate  $r$  will always increase; (iii) the retail price  $p$  does not change all the time; (b) however, the effects on launch price  $l$  are different in the two situations; (i) when  $c_V < H(\alpha)$  (i.e.  $l^* = l_S$ ), the launch price  $l$  will decrease; (ii) otherwise, it will increase. As the cost coefficient of effort  $k$  increases, the VM will exert less effort. So no matter the situation, the effort  $e$  always decreases with the increase of  $k$ . However, the changes in launch price  $l$  are different when  $c_V$  satisfies different conditions. That is because the body that determines the launch price has changed. When  $c_V < H(\alpha)$ , it is the SO to decide the launch price that she will decrease the contract price according to the decrease of effort  $e$ . But when  $c_V \geq H(\alpha)$ , the launch price is the VM's acceptance line, which means it is the VM to decide the launch price  $l$ , so he will increase the contract price to compensate for the increase of effort cost. For the premium rate, the IC sets it according to the effort  $e$ , so it will increase with the decreasing successful launch probability. As the retail price is not relative to the effort cost coefficient, there is no change in retail price  $p$ .

Then we analyze how penalty cost  $\theta$  affects these optimal outcomes. If the failed-launch penalty  $\theta$  increases, (a) no matter what the manufacturing cost of the vehicle  $c_V$  is, (i) the ef-

fort exerted by the VM  $e$  and the launch price  $l$  will always increase; (ii) the premium rate  $r$  will always decrease; (iii) the retail price  $p$  does not change all the time; (b) however, the effects on launch price  $l$  are different in the two situations; (i) when  $c_V < H(\alpha)$  (i.e.  $l^* = l_S$ ), the launch price  $l$  will decrease; (ii) otherwise, it will increase. Noted, the effect of  $\theta$  to  $e$  is similar to  $k$ , but the change is the opposite: no matter the situation, the effort  $e$  always increases with the increase of  $\theta$ . That is because the VM has to exert more effort to increase the successful launch probability to avoid the expensive failed-launch penalty  $\theta$ . The change of launch price  $l$  in these two situations is the same as  $k$  affects it. However, the internal cause of its change is different. When  $c_V < H(\alpha)$ , it is the SO to decide the launch price that she don't need to increase the launch price  $l$  as the VM will increase effort  $e$  spontaneously with the increasing of  $\theta$ . But when  $c_V \geq H(\alpha)$ , the launch price is the VM's acceptance line, which means it is the VM to decide the launch price  $l$ , so he will increase the contract price to compensate for the increase of failed-launch penalty. For the premium rate, the IC sets it according to the effort  $e$ , so it will decrease with the increasing successful launch probability. As the retail price is not relative to the penalty cost, there is no change in retail price  $p$ .

Under model I, by deriving different factors' sensitivity analyses on payoffs we have following findings: (a) If the cost coefficient of effort  $k$  increases, (i) VM's profit and social welfare always decrease; (ii) for the SO, in the situation  $c_V < H(\alpha)$ , her profit will increase when  $k < k_1$ , where  $k_1 = \frac{(1-\alpha)\theta}{2\alpha}$ , otherwise  $\pi_S^I$  will decrease when  $k \geq k_1$ ; in the other situation  $c_V \geq H(\alpha)$ , SO's profit decreases. (b) As the increasing of  $\theta$ , (i) SO's profit always increases; (ii) for the VM and society, in the situation  $c_V < H(\alpha)$ , their profits will increase when  $\theta$  satisfies with  $\theta < \theta_{V1}$  and  $\theta < \theta_{W1}$ , respectively, where  $\theta_{V1} = \frac{8k-2\alpha k}{1-\alpha}$  and  $\theta_{W1} = \frac{8k-6\alpha k}{3(1-\alpha)}$ , otherwise they both will decrease; in the other situation  $c_V \geq H(\alpha)$ ,  $\pi_S^I$  and  $SW$  will decreases.

### 3.2. Model IG: Satellite launch supply chain with government-subsidized insurance

Based on the practical observation of the real world, we build model IG in which we consider the situation that the government, aiming to promote the development of the commercial space industry, launches the commercial space launch insurance subsidy program. The event sequence is similar to the model I which is illustrated in Figure 2, but there is a change: after the IC decides



Table 3: Sensitivity analyses for Model I and Model IG.

	Model	Situation	$e^*$	$r^*$	$l^*$	$p^*$	$\pi_S$	$\pi_V$	$CS$	$SW$
$k \uparrow$	Model I	$c_V < H(\alpha)$	$\downarrow$	$\uparrow$	$\downarrow$	—	$\downarrow: k < k_1$ $\uparrow: k \geq k_1$	$\downarrow$	—	$\downarrow$
		$c_V \geq H(\alpha)$	$\downarrow$	$\uparrow$	$\uparrow$	—	$\downarrow$	—	—	$\downarrow$
	Model IG	$c_V < H(\alpha)$	$\downarrow$	$\uparrow$	$\downarrow: 0 < g < 1$ $-: g = 1$	—	$\downarrow: k < k_2$ $\uparrow: k \geq k_2$	$\downarrow$	—	$\downarrow$
		$c_V \geq H(\alpha)$	$\downarrow$	$\uparrow$	$\uparrow$	—				
$\theta \uparrow$	Model I	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\downarrow$	—	$\uparrow$	$\uparrow: \theta < \theta_{V1}$ $\downarrow: \theta \geq \theta_{V1}$	—	$\uparrow: \theta < \theta_{W1}$ $\downarrow: \theta \geq \theta_{W1}$
		$c_V \geq H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	—	$\uparrow$	—	—	$\uparrow$
	Model IG	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\downarrow$	—	$\uparrow$	$\uparrow: \theta < \theta_{V2}$ $\downarrow: \theta \geq \theta_{V2}$	—	$\uparrow: \theta < \theta_{W2}$ $\downarrow: \theta \geq \theta_{W2}$
		$c_V \geq H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	—	$\uparrow$	—	—	$\uparrow$
$g \uparrow$	Model IG	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	—	$\uparrow$	$\uparrow$	—	$\uparrow$
		$c_V \geq H(\alpha)$	—	—	—	—	$\uparrow$	—	—	$\uparrow$

To avoid complicated writing, we define  $k_1 = \frac{(1-\alpha)\theta}{2\alpha}$ ,  $k_2 = \frac{(1-\alpha)\theta}{2\alpha(1-g)}$ ,  $\theta_{V1} = \frac{8k-2\alpha k}{1-\alpha}$ ,  $\theta_{V2} = \frac{8k-2\alpha k(1-g)}{1-\alpha}$ ,  $\theta_{W1} = \frac{8k-6\alpha k}{3(1-\alpha)}$ ,  $\theta_{W2} = \frac{8k-6\alpha k(1-g)}{3(1-\alpha)}$ .

the premium rate  $r$ , the government will determine a subsidized rate  $g$ . So the only difference between model I and model IG is that the SO will obtain an insurance subsidy  $g$ . Before conducting analyses, we have Definition 3.1 which describes the “win-win” scenario.

**Definition 3.1.** *A win-win scenario is achieved under Model  $x$  if each member of the supply chain under Model  $x$  are all better off compared to the respective ones under Model NI.*

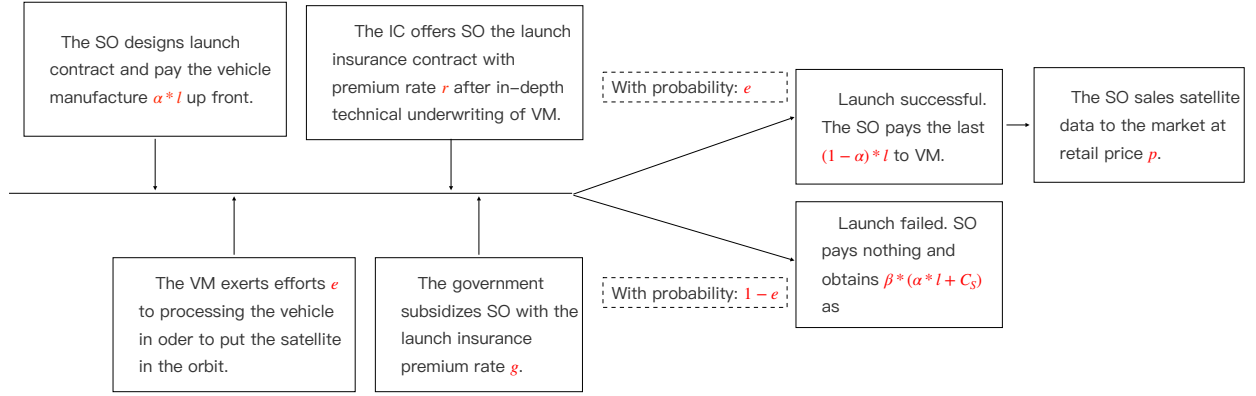


Figure 2: Sequence of events. SO :the satellite operator; VM: the vehicle manufacture; IC: the insurance company.

The market demand is given as follows:

$$D^{IG} = 1 \int_p^1 f(u) du = 1 - p \quad (11)$$

Then the members' payoffs can be measured as follows:

$$\begin{aligned} \pi_S^{IG} &= epD^{IG} - [\alpha + e(1 - \alpha)]l - (r - g)(c_S + \alpha l) + (1 - e)\beta(c_S + \alpha l) - c_S, \\ \pi_i^{IG} &= r(c_S + \alpha l) - (1 - e)\beta(c_S + \alpha l), \\ \pi_V^{IG} &= [\alpha + e(1 - \alpha)]l - (1 - e)\theta - (ke^2 + c_V), \\ s.t. \pi_V^{IG} &\geq 0 \end{aligned} \quad (12)$$

Following the similar derivation in 3.1, we obtain the equilibrium outcomes which are summarized in Lemma 3.2.

**Lemma 3.2.** *The equilibrium outcomes of Model IG are shown in Table 4.*

Table 4: The equilibrium outcomes in Model IG.

	$c_V < H(\alpha)$	$c_V \geq H(\alpha)$
Effort of VM exerting $e^*$	$\frac{\psi}{16(1-\alpha)k}$	$\frac{\omega-\alpha k}{(1-\alpha)k}$
Launch price $l^*$	$l^* = l_S = \frac{\psi-8\theta(1-\alpha)}{8(1-\alpha)^2}$	$l^* = l_{VA} = \frac{2\omega-2\alpha k-(1-\alpha)\theta}{(1-\alpha)^2}$
Retail price $p^*$	$\frac{1}{2}$	$\frac{1}{2}$
Premium rate $r^*$	$\beta(1 - \frac{\psi}{16(1-\alpha)k})$	$\beta \frac{k-\omega}{(1-\alpha)k}$
SO's profit $\pi_S^{IG}$	$\frac{\psi^2}{128(1-\alpha)^2k} + \frac{(1-g)\alpha\theta}{1-\alpha} - (1-g)c_S$	$\frac{(\omega-\alpha k)(\psi+8\alpha k-8\omega)}{4(1-\alpha)^2k} + \frac{(1-g)\alpha\theta}{1-\alpha} - (1-g)c_S$
VM's profit $\pi_V^{IG}$	$\frac{\psi^2+32\alpha k\psi}{256(1-\alpha)^2k} - \frac{\theta}{1-\alpha} - c_V$	0
Consumer surplus $CS^{IG}$	$\frac{1}{8}$	$\frac{1}{8}$
Social welfare $SW^{IG}$	$\frac{3\psi^2+32\alpha k\psi}{256(1-\alpha)^2k} - \frac{\theta[1-(1-g)\alpha]}{1-\alpha} - (1-g)c_S - c_V + \frac{1}{8}$	$\frac{(\omega-\alpha k)(\psi+8\alpha k-8\omega)}{4(1-\alpha)^2k} + \frac{(1-g)\alpha\theta}{1-\alpha} - (1-g)c_S + \frac{1}{8}$

To avoid complicated writing, we define  $\psi = (1-\alpha)(1+4\theta) - 8\alpha k(1-g)$ ,  $\omega = \sqrt{(1-\alpha)^2kc_V + \alpha^2k^2 - (1-\alpha)k\theta}$ .

Observing the optimal decisions of model IG are similar to that of model I, but there are three points worthy of notice. (i) When  $c_V < H(\alpha)$ , the successful launch probability  $e$  and launch price  $l$  increase as each has a positive increment, as  $\psi > \phi$ . The premium rate  $r$  will decrease, affected by government subsidy. (ii) When  $c_V \geq H(\alpha)$ , the successful launch probability, launch price, and the premium rate do not affect by the government subsidy. (iii) No matter the situation, the retail price doesn't change, which means the government subsidy program doesn't affect the market retail price. We will talk about the difference between model I and model IG in detail in Section 3.3.

We now report the sensitivity analysis performing as shown in Table 3. We find that the results of Model IG and Model I were very similar, but with three difference.

Firstly, if the cost coefficient of effort  $k$  increases, (i) when  $0 < g < 1$ , the launch price  $l$  will decrease in the first situation  $c_V < H(\alpha)$ ; however, when  $g = 1$  the launch price will not be affected by  $k$ ; (ii) the threshold  $k_2$  of SO's profit  $\pi_S^{IG}$  to change direction is higher than  $k_1$ , where  $k_2 = \frac{(1-\alpha)\theta}{2\alpha(1-g)}$ .

Secondly, if the launch-fail penalty  $\theta$  increases, in the situation  $c_V < H(\alpha)$ , the thresholds of  $\pi_V^{IG}$  and  $SW^{IG}$ ,  $\theta_{V2}$  and  $\theta_{W2}$  are both higher than these of model I, where  $\theta_{V2} = \frac{8k-2\alpha k(1-g)}{1-\alpha}$  and  $\theta_{W2} = \frac{8k-6\alpha k(1-g)}{3(1-\alpha)}$ . That means the VM and society can bear a higher penalty when the government

launch the subsidy program.

Thirdly, if the subsidy rate  $g$  increases, (i) when  $c_V < h(\alpha)$ , the successful launch probability  $e$  and the launch price  $l$  will increase, the premium rate  $r$  will decrease; the SO's profit  $\pi_S^{IG}$ , the VM's profit  $\pi_V^{IG}$  and social welfare  $SW^{IG}$  will increase; (ii) when  $c_V \geq H(\alpha)$ , all of the optimal decisions are not affected. (iii) no matter in which situation, the consumer surplus do not change which means the government subsidy program can't benefit the customers.

### 3.3. Values of government subsidies

In order to better explore the value of government subsidies, we explored  $V_i^{IG}$  as following, which represent the impacts that government subsidies bring to the successful launch probability, the premium rate, the launch price, the retail price, SO's profit, VM's profit, customer surplus, and the social welfare, respectively.

$$V_x^{IG} = x^{IG} - x^I \quad (13)$$

We report the results in Table 5 by comparing the equilibrium outcomes between model I and model IG. According to the sensitivity analysis, we obtain Proposition 3.1 and Proposition 3.2.

Table 5: Values of government subsidies.

Situation	$V_{e^*}^{IG}$	$V_{r^*}^{IG}$	$V_{l^*}^{IG}$	$V_{p^*}^{IG}$	$V_{SO}^{IG}$	$V_{VM}^{IG}$	$V_{CS}^{IG}$	$V_{SW}^{IG}$
$c_V < H(\alpha)$	$\frac{8\alpha g}{16(1-\alpha)}$	$\frac{-8\beta\alpha g}{16(1-\alpha)}$	$\frac{\alpha g}{(1-\alpha)^2}$	0	$\frac{\psi^2 - \phi^2}{128k(1-\alpha)^2} + \frac{g\alpha\theta}{1-\alpha} + gCS$	$\frac{\psi^2 - \phi^2 + 32\alpha k(\psi - \phi)}{256k(1-\alpha)^2}$	0	$\frac{3(\psi^2 - \phi^2) + 256\alpha k g[\alpha k + (1-\alpha)\theta]}{256k(1-\alpha)^2} + gCS$
$c_V \geq H(\alpha)$	0	0	0	0	$g[\frac{(\omega - \alpha k)\alpha}{2(1-\alpha)^2} - \frac{\alpha\theta}{1-\alpha} + c_S]$	0	0	$g[\frac{(\omega - \alpha k)\alpha}{2(1-\alpha)^2} - \frac{\alpha\theta}{1-\alpha} + c_S]$

**Proposition 3.1.** *Given  $\alpha, k, \theta, g$ :  $e^{IG} > e^I, r^{IG} < r^I, l^{IG} > l^I$  if and only if  $c_V < H(\alpha)$ .*

Proposition 3.1 indicates three points. Firstly, for given  $k, \theta$ , the launch insurance subsidy provided by the government can help to improve the successful launch probability  $e$  which is definitely helps to promote the benign development of the commercial satellite industry. Secondly, when the subsidy also helps to decrease the launch insurance rate  $r$ . This is because insurance companies set insurance rates based on break-even, so the larger the  $e$ , the smaller the  $r$ . From a

market perspective, government subsidies help soften the insurance market. Thirdly, the launch price in model IG also higher than that in model I. This is attributed to the fact that SO is more willing to pay higher launch fees after receiving subsidies. Higher launch fees also give VM an incentive to increase the probability of successful launches, thus forming a virtuous circle that helps to promote the development of the commercial satellite launch market.

Note, the above phenomenon occurs only in condition  $c_V < H(\alpha)$  which means that when the SO chooses an expensive vehicle ( $c_V > H(\alpha)$ ), government subsidies will not be able to form the above positive feedback closed loop in the market.

**Proposition 3.2.** *Given  $\alpha$ ,  $k$ ,  $\theta$ ,  $g$ :*

- (i)  $\pi_S^{IG} > \pi_S^I$ ,  $SW^{IG} > SW^I$ .
- (ii)  $\pi_V^{IG} > \pi_V^I$  if and only if  $c_V < H(\alpha)$
- (iii)  $CS^{IG} = CS^I$

Proposition 3.2 indicates three points. Firstly, for given  $k$ ,  $\theta$ , and  $g$ , the profit of SO and the social welfare in Model IG are always higher than in Model I. This means that when the launch insurance subsidy program is implemented, satellite operators and society always benefit. Mainly because the satellite operator is a direct beneficiary. Her earnings decided by the tradeoff between higher launch fees and higher launch success rates. Secondly, the profit of VM in Model IG is higher than in Model I if and only if  $c_V < H(\alpha)$ . The change of VM's profit depends on the tradeoff between higher effort cost and higher launch service income. However, when the cost of the vehicle is relatively high, VM will not benefit from the government subsidy. Thirdly, the consumer surplus in Model IG equals that in Model I, implying that government subsidies cannot benefit consumers.

As a remark, the implementation of government subsidies helps to improve the probability of successful launches, thereby promoting the formation of positive feedback in the commercial aviation industry. Moreover, It is important to note that the effective use of government subsidy is subsidizing satellite launch activities with inexpensive vehicles, which can achieve win-win scenario. Otherwise, subsidies can only increase the profit of satellite operators, but can not promote the launch success rate, which is not conducive to the optimal allocation of government funds.

#### 4. The case with blockchain technology

After exploring Model I and Model IG, we find that government subsidies for launch insurance do not benefit customers that the data demand  $D$  and retail price  $p$  remain unchanged in these two models. Luckily, the implementation of innovative technology, blockchain technology (BCT), injects new blood into the commercial space industry in two aspects: on one hand, BCT can enhance the security of satellite data which enhances trust among users; on the other hand, blockchain technology helps to improve the workflow efficiency of launch activities which helps to reduce the error rate, and thus increases the probability of successful launch. In this section, we analytical exploring how BCT improve the performance of the satellite launch supply chain.

In the real world, as depicted in Figure 3, the launching workflow is supported by BCT to deal with the complexities such as contracts, order tracking, parts assembly, shipments, design and test documents, test results data, near real-time data, workflows for approvals, auditing, launch and control. That means it will improve the data flow between different participants and capture the problem in time during the process. In other words, when information is shared adequately in the whole supply chain, it will help VM to save the effort cost to reach the ideal launch success probability, which is related to the symmetric and transparent information. (such as IBM and Cloud Constellation Corporation are working together to build a range of prototype solutions from Edge Computing in Space to exploring how blockchain can optimize the logistics and supply chain for the space tech industry (Altaf, 2019).

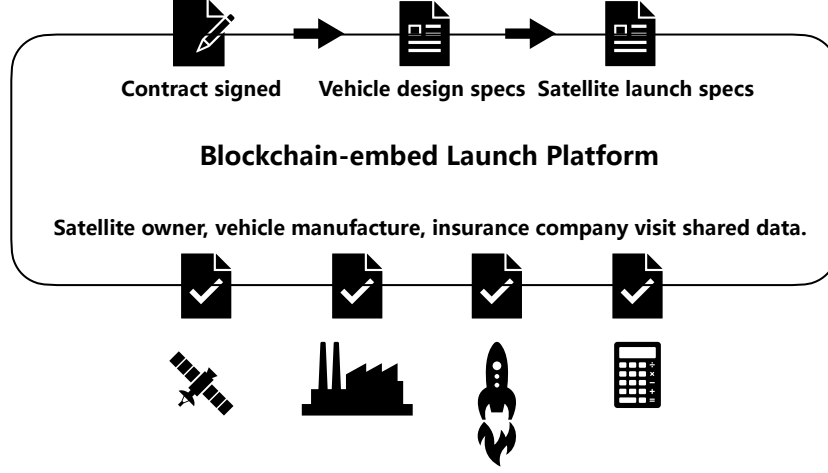


Figure 3: Satellite launch supported by blockchain platform.

Altaf (2019)

**Definition 4.1.** *An win-win scenario is achieved under Model  $x$  if the supply chain, consumers, and social welfare under Model  $x$  are all better off compared to the respective ones under Model  $NI$ .*

#### 4.1. Model B: Blockchain-embedded satellite launch supply chain with insurance

Compared to the case under Model I, all these parties will work together on the blockchain platform and the workflow will be more efficient which will be like (i) Launch data is made accessible via application program interfaces (APIs) for each of the participants on the nodes, and all interactions such as data download are tracked. (ii) All of the above activity is logged in the form of transactions in an immutable ledger database for auditing purposes to all the authorized interested participants. (iii) The data collected by the satellite will also record on BCT which cannot be tampered with. Figure 3 shows the whole launch success process in the avail of blockchain. Thus, the obvious advantage over Model I is that the transform data flow will decrease the effort cost and enhance the trust of customers. In other words, for the effort cost VM exerting to improve the launch successfully probability (denoted by  $k^B e^2$  for the case under Model B), it will be lower under Model B than under Model I, which means improve successful launch probability is cheaper with BCT than without BCT. We assume the blockchain platform provided by the third

party which will charge SO and VM for  $c_{SB}$  and  $c_{VB}$  respectively (Note: We assume the cost of BCT is lump-sum payment and the marginal cost of blockchain will be considered in the extended model Section 5.1). Before conducting analyses, we follow Luo (2020) to define the “all-win” scenario.

**Definition 4.2.** *An all-win scenario is achieved under Model  $x$  if the supply chain, customers, and social welfare under Model  $x$  are all better off compared to the respective ones under Model  $I$ .*

According to the assumption, we model the scenario with government subsidies and BCT. For customers, the benefits brought by BCT are characterized by factor  $b$  which will increase their utility. To be specific, the market demand can be written as follows:

$$D^B = 1 \int_{p-b}^1 f(u) du = 1 - p + b \quad (14)$$

Similar to Section 3.1, as the Stackelberg leader, SO sets the contract terms and the VM, as the follower, decides whether to accept the contract. Once the cooperation is signed, each of the participants gets a node which has a copy of ledger and smart contracts. As in Section 3.1, the SO prepays the supplier part of the contract price  $\alpha * l$  ahead. After launching, she will pay  $(1 - \alpha) * l$  upon successful delivery and pays 0 otherwise. Concerning risk, SO buy the launch insurance with premium rate  $r$  to compensate the damage if launch failed. Therefore, the members’ payoffs can be measured as follows:

$$\begin{aligned} \pi_S^B &= epD^B - [\alpha + e(1 - \alpha)]l - r(c_S + \alpha l) + (1 - e)\beta(c_S + \alpha l) - c_S - c_{SB}, \\ \pi_i^B &= r(c_S + \alpha l) - (1 - e)\beta(c_S + \alpha l), \\ \pi_V^B &= [\alpha + e(1 - \alpha)]l - (1 - e)\theta - (k^B e^2 + c_V) - c_{VB}, \\ s.t. \pi_V^B &\geq 0 \end{aligned} \quad (15)$$

As shown,  $\pi_S^B$  consists of five parts: (1) the income she will obtain once the satellite works in orbit ( $epD^B$ ), (2) the launch service price ( $[\alpha + e(1 - \alpha)]l$ ), (3) the premium SO pays for launch insurance( $r(c_S + \alpha l)$ ), (4) the compensate she will get once the launch failed( $(1 - e)\beta(c_S + \alpha l)$ ), (5) the cost of satellite and blockchain service,  $c_S$  and  $c_{SB}$ .



After receiving a contract with price  $l$  that is acceptable to VM, the cooperation is reached and a smart contract will be built. Then VM gets the node of checking the contract, which captures serious details to direct the conduction design, development, test and evaluation efficiently which cost  $c_V + c_{VB}$ . Also, he will get the prepayment  $\alpha * l$  from the SO. If the vehicle launch successfully, he receives the last  $(1 - \alpha) * l$  from the SO. If launching is not successful, the VM receives no payment. As shown,  $\pi_V^B$  consists of three parts: (1)the prepaid income and expected gain upon successful launch  $[\alpha + e(1 - \alpha)]l$ , (2)the expected loss of failure penalty in the event of launch failure  $(1 - e)\theta$ , (3)the whole cost  $k^B e^2 + c_V + c_{VB}$ . The non-negative profit constraint ensures the profitability of launch; otherwise, the VM will reject such a contract.

After a backward induction similar to the 3.1, we obtain Lemma 4.1.

**Lemma 4.1.** *The equilibrium outcomes of Model B are shown in Table 6.*

Table 6: The equilibrium outcomes in Model B.

	$c_V < H(\alpha)$	$c_V \geq H(\alpha)$
Effort of VM exerting $e^*$	$\frac{\eta}{16(1-\alpha)k^B}$	$\frac{\mu - \alpha k^B}{(1-\alpha)k^B}$
Launch price $l^*$	$l^* = l_S = \frac{\eta - 8\theta(1-\alpha)}{8(1-\alpha)^2}$	$l^* = l_{VA} = \frac{2\mu - 2\alpha k^B - (1-\alpha)\theta}{(1-\alpha)^2}$
Retail price $p^*$	$\frac{1+b}{2}$	$\frac{1+b}{2}$
Premium rate $r^*$	$\beta(1 - \frac{\eta}{16(1-\alpha)k^B})$	$\beta \frac{k^B - \mu}{(1-\alpha)k^B}$
SO's profit $\pi_S^B$	$\frac{\eta^2}{128(1-\alpha)^2 k^B} + \frac{\alpha\theta}{1-\alpha} - c_{SB}$	$\frac{(\mu - \alpha k^B)(\eta + 8\alpha k^B - 8\mu)}{4(1-\alpha)^2 k^B} + \frac{\alpha\theta}{1-\alpha} - c_S - c_{SB}$
VM's profit $\pi_V^B$	$\frac{\eta^2 + 32\alpha k^B \eta}{256(1-\alpha)^2 k^B} - \frac{\theta}{1-\alpha} - c_V - c_{VB}$	0
Consumer surplus $CS^B$	$\frac{(1+b)^2}{8}$	$\frac{(1+b)^2}{8}$
Social welfare $SW^B$	$\frac{3\eta^2 + 32\alpha k^B \eta}{256(1-\alpha)^2 k^B} - \theta - c_S - c_V - c_{SB} - c_{VB} + \frac{(1+b)^2}{8}$	$\frac{(\mu - \alpha k^B)(\phi + 8\alpha k^B - 8\mu)}{4(1-\alpha)^2 k^B} + \frac{\alpha\theta}{1-\alpha} - c_S - c_{SB} + \frac{(1+b)^2}{8}$

To avoid complicated writing, we define  $\eta = (1 - \alpha)(1 + b)^2 + 4(1 - \alpha)\theta - 8\alpha k^B$ ,  $\mu = \sqrt{(1 - \alpha)^2 k^B (c_V + c_{VB}) + \alpha^2 k^B^2} - (1 - \alpha)k^B \theta$ .

Outcomes in Lemma 4.1 are neat and similar to Lemma 3.1. There are two differences worth knowing. (i) First, when  $c_V < H(\alpha)$ , as  $k^B$  is less than  $k$  and  $\eta > \phi$ , the successful launch probability, the launch price are higher than in Model I; and the premium rate is lower than in Model I. (ii) When  $c_V \geq H(\alpha)$ , the equilibrium outcomes are not neat and cannot be directly compared which we will conduct analyze in detail in Section 4.2. (iii) Although the retail price is higher

compared with Model I, the consumer surplus increase with the implementation of BCT. Notably, the consumer surplus is only related to  $b$ , not to the cost of the blockchain. Therefore, as long as blockchain technology is adopted, the consumer surplus can be improved.

As the sensitivity outcomes shown in Table 3 we now conduct the analysis.

Table 7: Sensitivity analyses for Model I and Model B.

	Model	Situation	$e^*$	$r^*$	$l^*$	$p^*$	$\pi_S$	$\pi_V$	CS	SW
$k \uparrow$	Model I	$c_V < H(\alpha)$	$\downarrow$	$\uparrow$	$\downarrow$	$-$	$\downarrow: k < k_1$ $\uparrow: k \geq k_1$	$\downarrow$	$-$	$\downarrow$
		$c_V \geq H(\alpha)$	$\downarrow$	$\uparrow$	$\uparrow$	$-$	$\downarrow$	$-$	$-$	$\downarrow$
	Model B	$c_V < H(\alpha)$	$\downarrow$	$\uparrow$	$\downarrow$	$-$	$\downarrow: k < k_3$ $\uparrow: k \geq k_3$	$\downarrow$	$-$	$\downarrow$
		$c_V \geq H(\alpha)$	$\downarrow$	$\uparrow$	$\uparrow$	$-$				
$\theta \uparrow$	Model I	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\downarrow$	$-$	$\uparrow$	$\uparrow: \theta < \theta_{V1}$ $\downarrow: \theta \geq \theta_{V1}$	$-$	$\uparrow: \theta < \theta_{W1}$ $\downarrow: \theta \geq \theta_{W1}$
		$c_V \geq H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	$-$	$\uparrow$	$-$	$-$	$\uparrow$
	Model B	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\downarrow$	$-$	$\uparrow$	$\uparrow: \theta < \theta_{V3}$ $\downarrow: \theta \geq \theta_{V3}$	$-$	$\uparrow: \theta < \theta_{W3}$ $\downarrow: \theta \geq \theta_{W3}$
		$c_V \geq H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	$-$	$\uparrow$	$-$	$-$	$\uparrow$
$b \uparrow$	Model B	$c_V < H(\alpha)$	$\uparrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
		$c_V \geq H(\alpha)$	$-$	$-$	$-$	$\uparrow$	$-$	$-$	$\uparrow$	$\uparrow$

To avoid complicated writing, we define  $k_1 = \frac{(1-\alpha)\theta}{2\alpha}$ ,  $k_3 = \frac{(1-\alpha)[(1+b)^2+4\theta]}{8\alpha}$ ,  $\theta_{V1} = \frac{8k-2ak}{1-\alpha}$ ,  $\theta_{V3} = \frac{32k^B-(1-\alpha)(1+b)^2-8ak^B}{4(1-\alpha)}$ ,  $\theta_{W1} = \frac{8k-6ak}{3(1-\alpha)}$ ,  $\theta_{W3} = \frac{32k^B-3(1-\alpha)(1+b)^2-24ak^B}{12(1-\alpha)}$ .

By comparing the sensitivity analysis results of Model B and Model I, we find three differences: (i) Firstly, if the effort cost coefficient increase, when  $c_V < H(\alpha)$ , there exist a threshold  $k_3$ , where  $k_3 = \frac{(1-\alpha)[(1+b)^2+4\theta]}{8\alpha}$ . Thus SO's profit decreases as  $k^B$  increasing when  $k^B < k_3$ , otherwise  $\pi_S^{IG}$  decreases. Note  $k_3 > k_2$ , which means BCT raises the threshold of the SO to change the trend of her profits. (ii) Secondly, if the failed-launch penalty  $\theta$  increase, when  $c_V < H(\alpha)$ , the thresholds of VM's profit  $\theta_{V3}$  and social welfare  $\theta_{W3}$  also change, where  $\theta_{V3} = \frac{32k^B-(1-\alpha)(1+b)^2-8ak^B}{4(1-\alpha)}$  and  $\theta_{W3} = \frac{32k^B-3(1-\alpha)(1+b)^2-24ak^B}{12(1-\alpha)}$ . It is worth noting that the implementation of blockchain tech-

nology actually reduces the threshold of punishment to change the profit trend which means that the penalty tolerated by the VM and society is reduced, that is, once  $\theta > \theta_{V3}$  and  $\theta > \theta_{W3}$  both profits of them will decrease. (iii) If the benefits that blockchain brings to consumers  $b$  increases, (a) when  $c_V < H(\alpha)$ , the successful launch probability, launch price, retail price, member's profits, consumer surplus, and social welfare will all increase; the premium rate will decrease; (b) when  $c_V > H(\alpha)$ , although the retail price increase and the consumer surplus obtain for the customers will increase at all.

#### 4.2. Values of implementing BCT

Similar to Section 3.3, after deriving the equilibrium decisions of Model B, we further explore the values of BCT by modeling  $V_x^B$  as follows:

$$V_x^B = x^B - x^I \quad (16)$$

We report the results in Table 8 and Table 9, then obtain Proposition 4.1 and Proposition 4.2, which give the condition for adopting BCT.

Table 8: Values of BCT on optimal decisions.

	Situation	$V_{e^*}^B$	$V_{r^*}^B$	$V_{l^*}^B$	$V_{p^*}^B$
Value	$c_V < H(\alpha)$	$\frac{k[(1+b)^2+4\theta]-k^B(1+4\theta)}{16kk^B} > 0$	$-\beta \frac{k[(1+b)^2+4\theta]-k^B(1+4\theta)}{16kk^B} < 0$	$\frac{(1-\alpha)(b^2+2b)+8\alpha(k-k^B)}{8(1-\alpha)^2} > 0$	$\frac{b}{2} > 0$
	$c_V \geq H(\alpha)$	$\frac{k\mu-k^B\omega}{kk^B(1-\alpha)} > 0$	$-\beta \frac{k\mu-k^B\omega}{kk^B(1-\alpha)} < 0$	$\frac{2(\mu-\omega)+2\alpha(k-k^B)}{(1-\alpha)^2} > 0$	$\frac{b}{2} > 0$

Table 9: Values of BCT on members' payoffs.

	Situation	$V_{SO}^B$	$V_{VM}^B$	$V_{CS}^B$	$V_{SW}^B$
Value	$c_V < H(\alpha)$	$\frac{k\eta^2-k^B\phi^2}{128kk^B(1-\alpha)^2} - c_{SB}$	$\frac{k\eta^2-k^B\phi^2+32\alpha kk^B(\eta-\phi)}{256kk^B(1-\alpha)^2} - c_{VB}$	$\frac{b^2+2b}{8}$	$\frac{3k\eta^2-3k^B\phi^2+32\alpha kk^B(\eta-\phi)}{256kk^B(1-\alpha)^2} + \frac{b^2+2b}{8} - c_{SB} - c_{VB}$
	$c_V \geq H(\alpha)$	$\frac{k(\mu-\alpha k^B)[\eta-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\phi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2} - c_{SB}$	0	$\frac{b^2+2b}{8}$	$\frac{k(\mu-\alpha k^B)[\eta-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\phi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2} + \frac{b^2+2b}{8} - c_{SB}$

**Proposition 4.1.** Given  $\alpha, k^B, k, \theta, b$ :  $e^B > e^I, r^B < r^I, l^B > l^I, p^B > p^I$ .

Proposition 4.1 gives us four claims. Firstly, the optimal effort exerted by VM is higher after adopting blockchain technology, which directly leads to a higher launch success probability directly. That also implies that BCT helps to improve work efficiency. Secondly, the premium rate decreasing due to the successful launch probability increase. Thirdly, the launch price is higher with the support of BCT, mainly because the probability of successful launch increases and the SO is willing to pay higher fees. Fourthly, as shown the change of  $e$ ,  $r$ , and  $l$  are similar to Proposition 3.1, however, the retail price in Model B increases after implementing BCT which is different from Proposition 3.1. It is due to the higher utility that BCT bring to customers, so they are more willing to pay a higher retail price.

**Proposition 4.2.** *Given  $\alpha$ ,  $k^B$ ,  $k$ ,  $\theta$ ,  $b$ :*

- (i) *If  $c_{SB} \left( \begin{smallmatrix} < \\ = \\ > \end{smallmatrix} \right) \min\left\{ \frac{k\eta^2 - k^B\phi^2}{128kk^B(1-\alpha)^2}, \frac{k(\mu - \alpha k^B)[\eta - 8(\mu - \alpha k^B)] - k^B(\omega - \alpha k)[\phi - 8(\omega - \alpha k)]}{4kk^B(1-\alpha)^2} \right\}$ , then we have:  $V_{SO}^B \left( \begin{smallmatrix} > \\ = \\ < \end{smallmatrix} \right) 0$ ;*
- (ii) *When  $c_V < H(\alpha)$ , if  $c_{VB} \left( \begin{smallmatrix} < \\ = \\ > \end{smallmatrix} \right) \frac{k\eta^2 - k^B\phi^2 + 32\alpha k k^B(\eta - \phi)}{256kk^B(1-\alpha)^2}$ , then we have:  $V_{VM}^B \left( \begin{smallmatrix} > \\ = \\ < \end{smallmatrix} \right) 0$ ; when  $c_V \geq H(\alpha)$ ,  $V_{VM}^B \equiv 0$*
- (iii)  $V_{CS}^B > 0$
- (iv) *When  $c_V < H(\alpha)$ , if  $c_{SB} + c_{VB} \left( \begin{smallmatrix} < \\ = \\ > \end{smallmatrix} \right) \frac{3k\eta^2 - 3k^B\phi^2 + 32\alpha k k^B(\eta - \phi)}{256kk^B(1-\alpha)^2} + \frac{b^2 + 2b}{8}$ , then we have  $V_{SW}^B \left( \begin{smallmatrix} > \\ = \\ < \end{smallmatrix} \right) 0$ ; when  $c_V \geq H(\alpha)$ , if  $c_{SB} \left( \begin{smallmatrix} < \\ = \\ > \end{smallmatrix} \right) \frac{k(\mu - \alpha k^B)[\eta - 8(\mu - \alpha k^B)] - k^B(\omega - \alpha k)[\phi - 8(\omega - \alpha k)]}{4kk^B(1-\alpha)^2} + \frac{b^2 + 2b}{8}$ , then we have  $V_{SW}^B \left( \begin{smallmatrix} > \\ = \\ < \end{smallmatrix} \right) 0$ .*

As shown above, Proposition 4.2 gives us four neat findings.

Firstly, it gives the threshold of blockchain cost for SO, indicating that if the cost of implementing blockchain technology is high, then launching through the BCT platform is not profitable. That is because the loss of paying for blockchain cannot be offset by the benefits of improving the quality of data flow and higher retail income. Actually, there are two different thresholds for the SO to decide whether implement BCT in two situations. However, once BCT costs are pretty low, it is always profitable for the SO to use blockchain.

Secondly, it also gives the threshold and condition for VM using blockchain. When  $c_V < H(\alpha)$ , if the cost of BCT is low, VM has space to make a profit. However, when  $c_V$  is high, it is unprofitable for VM to apply BCT. It lies in the launch price SO offering only matches VM's acceptance level, and his payoff is zero in this situation.

Thirdly, with the help of BCT, the consumer surplus increases, which means customers will benefit more, although they have to pay higher retail prices.

Fourthly, as shown in Proposition 4.2, the social welfare will be improved with the adoption of blockchain as long as the cost of BCT is lower than a specific threshold.

As a remark, comparing with the value of government subsidies in Section 3.3, the successful launch probability will always be improved under the value of adopting BCT whether SO chooses a cost-effective vehicle for launch or not, but not always under government subsidies' values. This is significantly different from the values of government subsidies in Proposition 3.1. Besides, the BCT helps achieve an all-win situation when the cost of BCT is relatively low for supply chain members. In conclusion, the government may consider providing financial support for sponsoring the supply chain adopting BCT to improve the successful launch rate and achieve all-win.

#### 4.3. Model BG: Blockchain-embedded satellite launch supply chain with government-subsidized insurance

In this section, we will investigate the government-subsidized launch insurance and the BCT in commercial space launch supply chain represented by Model BG.

$$\begin{aligned}
\pi_S^{BG} &= epD^{BG} - [\alpha + e(1 - \alpha)]l - r(c_S + \alpha l) + (1 - e)\beta(c_S + \alpha l) - c_S - c_{SB}, \\
\pi_S^{BG} &= (r - g)(c_S + \alpha l) - (1 - e)\beta(c_S + \alpha l), \\
\pi_V^{BG} &= [\alpha + e(1 - \alpha)]l - (1 - e)\theta - (k^B e^2 + c_V) - c_{VB}, \\
s.t. \quad \pi_V^B &\geq 0
\end{aligned} \tag{17}$$

As the assumption is similar to Model IG and Model B, we conduct the backward induction and obtain Lemma 4.2.

**Lemma 4.2.** *The equilibrium outcomes of Model BG are shown in Table 10.*

The equilibrium outcomes in Lemma 4.2 are similar to that in Lemma 3.2 but with two differences worth knowing. (i) First, as  $k^B$  is less than  $k$  leading to denominator decreases, as  $\lambda > \psi$  leading to numerator increases, thus the successful launch probability  $e$  and the launch price  $l$  are higher than in Model IG; and the premium rate  $r$  is lower compared with Model IG. (ii) Although

Table 10: The equilibrium outcomes in Model BG.

	$c_V < H(\alpha)$	$c_V \geq H(\alpha)$
Effort of VM exerting $e^*$	$\frac{\lambda}{16(1-\alpha)k^B}$	$\frac{\mu-\alpha k^B}{(1-\alpha)k^B}$
Launch price $l^*$	$l^* = l_S = \frac{\lambda-8\theta(1-\alpha)}{8(1-\alpha)^2}$	$l^* = l_{VA} = \frac{2\mu-2\alpha k^B-(1-\alpha)\theta}{(1-\alpha)^2}$
Retail price $p^*$	$\frac{1+b}{2}$	$\frac{1+b}{2}$
Premium rate $r^*$	$\beta(1 - \frac{\lambda}{16(1-\alpha)k^B})$	$\beta \frac{k-\mu}{(1-\alpha)k^B}$
SO's profit $\pi_S^{BG}$	$\frac{\lambda^2}{128(1-\alpha)^2 k^B} + \frac{(1-g)\alpha\theta}{1-\alpha} - (1-g)c_S - c_{SB}$	$\frac{(\mu-\alpha k^B)(\lambda+8\alpha k^B-8\mu)}{4(1-\alpha)^2 k^B} + \frac{(1-g)\alpha\theta}{1-\alpha} - (1-g)c_S - c_{SB}$
VM's profit $\pi_V^{BG}$	$\frac{\lambda^2+32\alpha k^B \lambda}{256(1-\alpha)^2 k^B} - \frac{\theta}{1-\alpha} - c_V - c_{VB}$	0
Consumer surplus $CS^{BG}$	$\frac{(1+b)^2}{8}$	$\frac{(1+b)^2}{8}$
Social welfare $SW^{BG}$	$\frac{3\lambda^2+32\alpha k^B \lambda}{256(1-\alpha)^2 k^B} - \frac{\theta[1-(1-g)\alpha]}{1-\alpha} - (1-g)c_S - c_V - c_{SB} - c_{VB} + \frac{(1+b)^2}{8}$	$\frac{(\mu-\alpha k^B)(\lambda+8\alpha k^B-8\mu)}{4(1-\alpha)^2 k^B} + \frac{(1-g)\alpha\theta}{1-\alpha} - (1-g)c_S - c_{SB} + \frac{(1+b)^2}{8}$

To avoid complicated writing, we define  $\lambda = (1-\alpha)(1+b)^2 + 4(1-\alpha)\theta - 8\alpha k^B(1-g)$ ,  $\mu = \sqrt{(1-\alpha)^2 k^B(c_V + c_{VB}) + \alpha^2 k^B^2 - (1-\alpha)k^B\theta}$ .

the retail price  $p$  is higher compared with Model IG, the consumer surplus eventually increase due to a greater increase in market demand with the adoption of BCT. Noted, the consumer surplus is only related to  $b$ , not to the cost of the blockchain. Therefore, as long as blockchain technology is adopted, the consumer surplus can be improved.

#### 4.4. Values of implementing BCT with government subsidies

After deriving the equilibrium decisions in the supply chains under Models G and Model BG, we now explore the values of blockchain technology with government subsidies.

$$V_x^{BG} = x^{BG} - x^{IG} \quad (18)$$

By comparing Model BG and Model IG, we report the results in Table 11 and Table 12 which leading to Proposition 4.3 and Proposition 4.4.

**Proposition 4.3.** Given  $k^B$ ,  $k$ ,  $\theta$ ,  $g$ ,  $b$ :  $e^{BG} > e^{IG}$ ,  $r^{BG} < r^{IG}$ ,  $l^{BG} > l^{IG}$ ,  $p^{BG} > p^{IG}$ .

As shown, the results in Proposition 4.3 are similar to Proposition 4.1. It indicates that for given  $k^B$ ,  $k$ ,  $\theta$ ,  $g$ , and  $b$ , under the government subsidies, the BCT helps to increase the probability of successful launch  $e$ , the retail price  $p$ , and decrease the premium rate  $r$  under the government

subsidies. Note that in the case of government subsidies, when the cost of vehicle is high, the effect of blockchain in increasing launch price is weakened compared to the absence of subsidies with a decrease of  $\frac{\alpha g(k-k^B)}{(1-\alpha)^2}$  as shown in Table 13. In addition, BCT has the same impact on each optimal decision, whether there is government subsidy or not.

**Proposition 4.4.** *Given  $k^B$ ,  $k$ ,  $\theta$ ,  $g$ ,  $b$ :*

- (i) *If  $c_{SB} \left( \begin{smallmatrix} \leq \\ \equiv \\ \geq \end{smallmatrix} \right) \min\left\{ \frac{k\lambda^2 - k^B\psi^2}{128kk^B(1-\alpha)^2}, \frac{k(\mu - \alpha k^B)[\lambda - 8(\mu - \alpha k^B)] - k^B(\omega - \alpha k)[\psi - 8(\omega - \alpha k)]}{4kk^B(1-\alpha)^2} \right\}$ , then we have:  $V_{SO}^{BG} \left( \begin{smallmatrix} > \\ \equiv \\ < \end{smallmatrix} \right) 0$ ;*
- (ii) *When  $c_V < H(\alpha)$ , if  $c_{VB} \left( \begin{smallmatrix} \leq \\ \equiv \\ \geq \end{smallmatrix} \right) \frac{k\lambda^2 - k^B\psi^2 + 32\alpha k k^B(\lambda - \psi)}{256kk^B(1-\alpha)^2}$ , for  $c_V < H(\alpha)$  then we have:  $V_{VM}^{BG} \left( \begin{smallmatrix} > \\ \equiv \\ < \end{smallmatrix} \right) 0$ ;  
when  $c_V \geq H(\alpha)$ ,  $V_{VM}^{BG} \equiv 0$*
- (iii)  $V_{CS}^{BG} > 0$
- (iv) *When  $c_V < H(\alpha)$ , if  $c_{SB} + c_{VB} \left( \begin{smallmatrix} \leq \\ \equiv \\ \geq \end{smallmatrix} \right) \frac{3k\lambda^2 - 3k^B\psi^2 + 32\alpha k k^B(\lambda - \psi)}{256kk^B(1-\alpha)^2} + \frac{b^2 + 2b}{8}$ , then we have  $V_{SW}^{BG} \left( \begin{smallmatrix} > \\ \equiv \\ < \end{smallmatrix} \right) 0$ ; when  $c_V \geq H(\alpha)$ , if  $c_{SB} \left( \begin{smallmatrix} \leq \\ \equiv \\ \geq \end{smallmatrix} \right) \frac{k(\mu - \alpha k^B)[\lambda - 8(\mu - \alpha k^B)] - k^B(\omega - \alpha k)[\psi - 8(\omega - \alpha k)]}{4kk^B(1-\alpha)^2} + \frac{b^2 + 2b}{8}$ , then we have  $V_{SW}^{BG} \left( \begin{smallmatrix} > \\ \equiv \\ < \end{smallmatrix} \right) 0$ .*

The values of BCT under the case of government subsidies in Proposition 4.4 are similar to the role of BCT without subsidies in Proposition 4.2. Compared with Model IG, the BCT in Model BG helps to increase the profit of SO and the welfare of society when the cost of BCT is not high. For the VM, when  $c_V < H(\alpha)$ , he will benefit from the adoption of BCT if it doesn't cost too much. Otherwise, it is not profitable for him to implement BCT. For customers, the consumer surplus will be higher once the BCT is adopted.

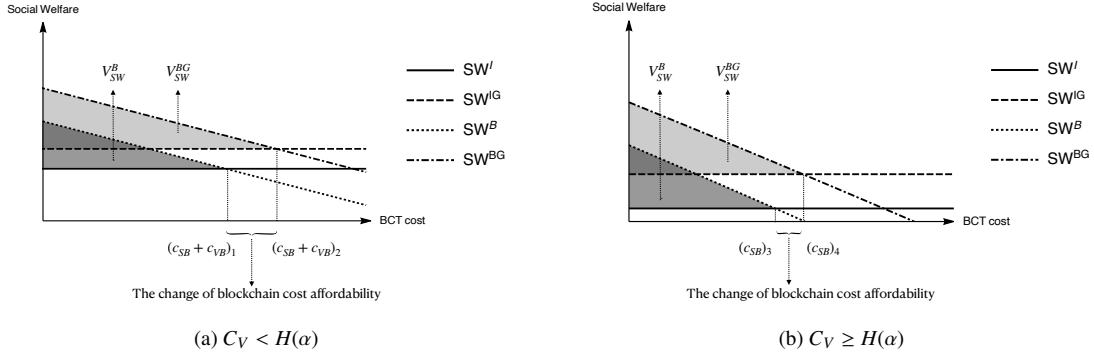


Figure 4: The value of blockchain for social welfare with (i.e.,  $V_{SW}^{GB}$ : the light grey area with the overlapping part enclosed by line  $SW^{IG}$  and line  $SW^{BG}$ ) and without government subsidies (i.e.,  $V_{SW}^B$ : the dark grey area with the overlapping part enclosed by line  $SW^I$  and line  $SW^B$ ), when  $k = 0.8$ ,  $k^B = 0.6$ ,  $c_V = 0.01$ ,  $c_S = 0.1$ ,  $\theta = 0.5$ ,  $b = 0.9$ ,  $g = 0.5$ ,  $\alpha = 0.2$ ,  $(c_{SB} + c_{VB})_1 = \frac{3k\eta^2 - 3k^B\phi^2 + 32\alpha k k^B(\eta - \phi)}{256kk^B(1-\alpha)^2} + \frac{b^2 + 2b}{8}$ ,  $(c_{SB} + c_{VB})_2 = \frac{3k\lambda^2 - 3k^B\psi^2 + 32\alpha k k^B(\lambda - \psi)}{256kk^B(1-\alpha)^2} + \frac{b^2 + 2b}{8}$ ,  $(c_{SB})_3 = \frac{k(\mu - \alpha k^B)[\eta - 8(\mu - \alpha k^B)] - k^B(\omega - \alpha k)[\phi - 8(\omega - \alpha k)]}{4kk^B(1-\alpha)^2} + \frac{b^2 + 2b}{8}$ ,  $(c_{SB})_4 = \frac{k(\mu - \alpha k^B)[\lambda - 8(\mu - \alpha k^B)] - k^B(\omega - \alpha k)[\psi - 8(\omega - \alpha k)]}{4kk^B(1-\alpha)^2} + \frac{b^2 + 2b}{8}$ .

Note that the blockchain usage thresholds given by Proposition 4.4 are higher than that listed in Proposition 4.2. This means, the adoption of BCT in the case of government subsidies can improve the affordability of blockchain costs. From another point of view, the adoption of blockchain can also amplify the efficiency of government subsidies with amplifications shown in Table 14.

In conclusion, adopting BCT under government subsidies can increase the successful launch probability and benefit all the members to achieve all-win when the cost of BCT is not high compared to the case with government subsidies (Model IG). Besides, compared with the value of BCT without subsidies ( $V_x^B$ ), the affordability of BCT will be improved by government subsidies, and the increase in launch price will lower, which means the value of the government will be magnify as shown in Figure 4 (e.t.,  $(c_{SB} + c_{VB})_2 > (c_{SB} + c_{VB})_1$  and  $(c_{SB})_4 > (c_{SB})_3$ ). It implies that government subsidies are more likely to be preferred after adopting BCT.

Table 11: Values of BCT with government subsidies on optimal decisions.

	Situation	$V_{e^*}$	$V_{r^*}^{BG}$	$V_{r^*}$	$V_{p^*}$
Value	$c_V < H(\alpha)$	$\frac{k[(1+b)^2 + 4\theta] - k^B(1+4\theta)}{16kk^B} > 0$	$-\beta \frac{k[(1+b)^2 + 4\theta] - k^B(1+4\theta)}{16kk^B} < 0$	$\frac{(1-\alpha)(b^2 + 2b) + 8\alpha(1-g)(k - k^B)}{8(1-\alpha)^2} > 0$	$\frac{b}{2} > 0$
	$c_V \geq H(\alpha)$	$\frac{k\mu - k^B\omega}{kk^B(1-\alpha)} > 0$	$-\beta \frac{k\mu - k^B\omega}{kk^B(1-\alpha)} < 0$	$\frac{2(\mu - \omega) + 2\alpha(k - k^B)}{(1-\alpha)^2} > 0$	$\frac{b}{2} > 0$



Table 12: Values of BCT with government subsidies on members' payoffs.

	Situation	$V_{SO}^{BG}$	$V_{VM}^{BG}$	$V_{CS}^{BG}$	$V_{SW}^{BG}$
Value	$c_V < H(\alpha)$	$\frac{k\lambda^2 - k^B\psi^2}{128kk^B(1-\alpha)^2} - c_{SB}$	$\frac{k\lambda^2 - k^B\psi^2 + 32\alpha kk^B(\lambda - \psi)}{256kk^B(1-\alpha)^2} - c_{VB}$	$\frac{b^2 + 2b}{8}$	$\frac{3k\lambda^2 - 3k^B\psi^2 + 32\alpha kk^B(\lambda - \psi)}{256kk^B(1-\alpha)^2} + \frac{b^2 + 2b}{8} - c_{SB} - c_{VB}$
	$c_V \geq H(\alpha)$	$\frac{k(\mu - \alpha k^B)[\lambda - 8(\mu - \alpha k^B)] - k^B(\omega - \alpha k)[\psi - 8(\omega - \alpha k)]}{4kk^B(1-\alpha)^2} - c_{SB}$	0	$\frac{b^2 + 2b}{8}$	$\frac{k(\mu - \alpha k^B)[\lambda - 8(\mu - \alpha k^B)] - k^B(\omega - \alpha k)[\psi - 8(\omega - \alpha k)]}{4kk^B(1-\alpha)^2} + \frac{b^2 + 2b}{8} - c_{SB}$

Table 13: The increases in the value of BCT on optimal decisions under government subsidies.

	Situation	$\Delta V_{e^*}^B$	$\Delta V_{r^*}^B$	$\Delta V_{l^*}^B$	$\Delta V_{p^*}^B$
$\Delta \text{Value}$	$c_V < H(\alpha)$	0	0	$\frac{-\alpha g(k - k^B)}{(1-\alpha)^2} < 0$	0
	$c_V \geq H(\alpha)$	0	0	0	0

## 5. Extended Models

### 5.1. Marginal cost of implementing BCT

In the models above, we assume the cost of BCT is a lump sum neglecting the marginal cost of BCT to acquire and store data, which may not be accurate in practice. Thus, we extend the blockchain models considering the marginal cost of implementing BCT denoted by  $c$ . We verify the robustness of our findings by exploring two cases that (i) blockchain-embedded satellite launch supply chain with insurance (Model B-c) (ii) blockchain-embedded satellite launch supply chain with government-subsidized insurance (Model BG-c).

#### 5.1.1. Model B-c

According to the setting, the market demand of Model B-c can be written as follows:

Table 14: The increases in the value of BCT on on members' payoffs under government subsidies.

	Situation	$\Delta V_{SO}^B$	$\Delta V_{VM}^B$	$\Delta V_{CS}^B$	$\Delta V_{SW}^B$
$\Delta \text{Value}$	$c_V < H(\alpha)$	$\frac{\alpha g[(1-\alpha)b^2 + 2(1-\alpha)b + 4\alpha(2-g)(k - k^B)]}{8(1-\alpha)^2} > 0$	$\frac{\alpha g[(1-\alpha)b^2 + 2(1-\alpha)b - 4\alpha(2+g)(k - k^B)]}{16(1-\alpha)^2} > 0$	0	$\frac{\alpha g[3(1-\alpha)b^2 + 6(1-\alpha)b + 4\alpha(2-3g)(k - k^B)]}{16(1-\alpha)^2} > 0$
	$c_V \geq H(\alpha)$	$\frac{2\alpha g[\alpha(k - k^B) - \omega + \mu]}{(-1+\alpha)^2} > 0$	0	0	$\frac{2\alpha g[\alpha(k - k^B) - \omega + \mu]}{(-1+\alpha)^2} > 0$

$$D^{B-c} = 1 \int_{p^{B-c}-b}^1 f(u) du = 1 - p^{B-c} + b \quad (19)$$

Therefore, the members' payoffs can be measured as follows:

$$\begin{aligned} \pi_S^{B-c} &= e(p-c)D^{B-c} - [\alpha + e(1-\alpha)]l - (r-g)(c_S + \alpha l) + (1-e)\beta(c_S + \alpha l) - c_S - c_{SB}, \\ \pi_I^{B-c} &= r(c_S + \alpha l) - (1-e)\beta(c_S + \alpha l), \\ \pi_V^{B-c} &= [\alpha + e(1-\alpha)]l - (1-e)\theta - (k^B e^2 + c_V) - c_{VB}, \end{aligned} \quad (20)$$

$$s.t. \pi_V^{B-c} \geq 0.$$

Note, the only difference between Model B-c and Model B is that the BCT's marginal cost occurs to SO. We solve the derivation and summarize the outcomes in Table 15.

Table 15: The equilibrium outcomes in Model B-c.

	$c_V < H(\alpha)$	$c_V \geq H(\alpha)$
Effort of VM exerting $e^*$	$\frac{\eta-C}{16(1-\alpha)k^B}$	$\frac{\mu-\alpha k^B}{(1-\alpha)k^B}$
Launch price $l^*$	$l^* = l_S = \frac{\eta-8\theta(1-\alpha)-C}{8(1-\alpha)^2}$	$l^* = l_{VA} = \frac{2\mu-2\alpha k^B-(1-\alpha)\theta}{(1-\alpha)^2}$
Retail price $p^*$	$\frac{1+b+c}{2}$	$\frac{1+b+c}{2}$
Premium rate $r^*$	$\beta(1 - \frac{\eta-C}{16(1-\alpha)k^B})$	$\beta \frac{k^B-\mu}{(1-\alpha)k^B}$
SO's profit $\pi_S^{B-c}$	$\frac{\eta^2-C(C-2\eta)}{128(1-\alpha)^2 k^B} + \frac{\alpha\theta}{1-\alpha} - c_S - c_{SB}$	$\frac{(\mu-\alpha k^B)(\eta+8\alpha k^B-8\mu-C)}{4(1-\alpha)^2 k^B} + \frac{\alpha\theta}{1-\alpha} - c_S - c_{SB}$
VM's profit $\pi_V^{B-c}$	$\frac{\eta^2+32\alpha k^B \eta-C(C-2\eta-32\alpha k^B)}{256(1-\alpha)^2 k^B} - \frac{\theta}{1-\alpha} - c_V - c_{VB}$	0
Consumer surplus $CS^{B-c}$	$\frac{(1+b-c)^2}{8}$	$\frac{(1+b-c)^2}{8}$
Social welfare $SW^{B-c}$	$\frac{3\eta^2+32\alpha k^B \eta-C(3C-6\eta-32\alpha k^B)}{256(1-\alpha)^2 k^B} - \theta - c_S - c_V - c_{SB} - c_{VB} + \frac{(1+b-c)^2}{8}$	$\frac{(\mu-\alpha k^B)(\phi+8\alpha k^B-8\mu-C)}{4(1-\alpha)^2 k^B} + \frac{\alpha\theta}{1-\alpha} - c_S - c_{SB} + \frac{(1+b-c)^2}{8}$

To avoid complicated writing, we define  $\eta = (1-\alpha)(1+b)^2 + 4(1-\alpha)\theta - 8\alpha k^B$ ,  $\mu = \sqrt{(1-\alpha)^2 k^B (c_V + c_{VB}) + \alpha^2 k^{B^2}} - (1-\alpha)k^B \theta$ ,  $C = (1-\alpha)c(2+2b-c)$ .

To explore the effect of blockchain marginal cost on the equilibrium outcomes, we compare Model B-c with Model B and obtain Proposition 5.1.

**Proposition 5.1.** *Under Model B-c, the satellite launch supply chain adopts the BCT with insurance considering the marginal cost of BCT.*

Compared with Model B, (i) when  $c_V < H(\alpha)$ , (a)  $e^{B-c} < e^B$ ,  $l^{B-c} < l^B$ ,  $r^{B-c} > r^B$ ,  $p^{B-c} > p^B$ ; (b) if  $0 < c < 1+b - \sqrt{\frac{(1-\alpha)(1+b)^2-2\eta}{1-\alpha}}$ ,  $\pi_S^{B-c} > \pi_S^B$ ; otherwise,  $\pi_S^{B-c} \leq \pi_S^B$ ; if  $0 < c < 1+b -$

$$\sqrt{\frac{(1-\alpha)(1+b)^2-2(\eta+16\alpha k^B)}{1-\alpha}}, \pi_V^{B-c} > \pi_V^B; \text{ otherwise, } \pi_V^{B-c} \leq \pi_V^B; CS^{B-c} < CS^B; \text{ if } 0 < c < 1 + b - \sqrt{\frac{3(1-\alpha)(1+b)^2-2(3\eta+16k^B)}{3(1-\alpha)}}, \pi_{SW}^{B-c} > \pi_{SW}^B; \text{ otherwise, } \pi_{SW}^{B-c} \leq \pi_{SW}^B;$$

(ii) when  $c_V \geq H(\alpha)$ , (a)  $e^{B-c} = e^B$ ,  $l^{B-c} = l^B$ ,  $r^{B-c} = r^B$ ,  $p^{B-c} > p^B$ ; (b)  $\pi_S^{B-c} < \pi_S^B$ ;  $\pi_V^{B-c} = \pi_V^B = 0$ ;  $CS^{B-c} < CS^B$ ;  $\pi_{SW}^{B-c} < \pi_{SW}^B$ .

Proposition 5.1 indicates the effect of marginal cost of BCT by comparing Model B-c and Model B and give us new findings. It implies that in the case of  $c_V < H(\alpha)$ , the presence of the BCT marginal cost in the satellite launch supply chain means that SO prefers to pay a lower launch price, the VM exerts less effort to make the launch successful, the SO has to bear higher insurance rates, and consumers suffer a higher retail price. Since the marginal cost of BCT can lead to both an increase in retail price and a decrease in market demand, there exists thresholds regarding  $c$  for comparing members' profits between Model B-c and Model B. The tradeoff between the higher retail price and the lower market demand affects the change in total profit eventually. In the first case ( $c_V < H(\alpha)$ ), when the marginal cost is low, the supply chain participants in Model B-c have higher returns. Once the marginal cost exceeds a certain threshold, the payoffs of participants in Model B-c are lower than those in Model B. For consumers, once the marginal cost exists, consumer surplus is impaired because they need to pay a higher retail price.

However, when the SO chooses an expensive vehicle ( $c_V \geq H(\alpha)$ ), only the retail price is higher than in Model B, and the others are equal to that in Model B, which do not affect by  $c$ . This is because the VM sets the launch price instead of the SO in this scenario. Therefore, transferring the marginal cost of BCT to consumers is the only way for the SO to make a profit. This treatment is similar to transferring the variable price per product unit in a traditional supply chain. For the payoff, all participants except the VM suffer a loss of profits due to the presence of marginal costs. The VM only maintains break-even in this scenario, the same as Model B.

Further, to explore whether the value of BCT to the launch supply chain changes after considering marginal costs, i.e., to verify the robustness of Proposition 4.1 and Proposition 4.2, we conduct comparison between Models B-c and Model I nextly.

**Proposition 5.2.** *Under Model B-c, the satellite launch supply chain adopts the BCT with insurance considering the marginal cost of BCT.*

Compared with Model I, (i) when  $c_V < H(\alpha)$ , (a) if  $0 < c < 1 + b - \sqrt{\frac{(1+4\theta)k^B}{k}} - 4\theta$ ,  $e^{B-c} > e^I$ ,  $r^{B-c} < r^I$ ; otherwise,  $e^{B-c} \leq e^I$ ,  $r^{B-c} \geq r^I$ ; if  $0 < c < 1 + b - \sqrt{1 - \frac{8\alpha(k-k^B)}{1-\alpha}}$ ,  $l^{B-c} > l^I$ ; otherwise,  $l^{B-c} \leq l^I$ ; if  $0 < c < b$ ,  $p^{B-c} > p^I$ , otherwise,  $p^{B-c} \leq p^I$  (b) if  $0 < c < 1 + b - \sqrt{\frac{(1-\alpha)(1+b)^2-2\eta}{1-\alpha}}$  and  $c_{SB} < \frac{k\eta^2-k^B\phi^2}{128kk^B(1-\alpha)^2}$ ,  $\pi_S^{B-c} > \pi_S^I$ ; otherwise,  $\pi_S^{B-c} \leq \pi_S^I$ ; if  $0 < c < 1 + b - \sqrt{\frac{(1-\alpha)(1+b)^2-2\eta-32\alpha k^B}{1-\alpha}}$  and  $c_{VB} < \frac{k\eta^2-k^B\phi^2+32\alpha k^B(\eta-\phi)}{256kk^B(1-\alpha)^2}$ ,  $\pi_V^{B-c} > \pi_V^I$ ; otherwise,  $\pi_V^{B-c} \leq \pi_V^I$ ; if  $0 < c < b$ ,  $CS^{B-c} > CS^I$ ; otherwise,  $CS^{B-c} \leq CS^I$ ; if  $0 < c < 1 + b - \sqrt{\frac{3(1-\alpha)(1+b)^2-6\eta-32\alpha k^B}{3(1-\alpha)}}$  and  $c_{SB} + c_{VB} < \frac{3k\eta^2-3k^B\phi^2+32\alpha k^B(\eta-\phi)}{256kk^B(1-\alpha)^2} + \frac{b^2+2b}{8}$ ,  $SW^{B-c} > SW^I$ ; otherwise,  $SW^{B-c} \leq SW^I$ .

(ii) when  $c_V \geq H(\alpha)$ , (a)  $e^{B-c} > e^I$ ,  $l^{B-c} > l^I$ ,  $r^{B-c} < r^I$ ; if  $0 < c < b$ ,  $p^{B-c} > p^I$ ; otherwise,  $p^{B-c} \leq p^I$ ; (b) if  $c_{SB} < \frac{k(\mu-\alpha k^B)[\eta-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\phi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2}$ ,  $\pi_S^{B-c} > \pi_S^I$ ; otherwise,  $\pi_S^{B-c} \leq \pi_S^I$ ;  $\pi_V^{B-c} = \pi_V^I = 0$ ; if  $0 < c < b$ ,  $CS^{B-c} > CS^I$ ; otherwise,  $CS^{B-c} \leq CS^I$ ; if  $c_{SB} < \frac{k(\mu-\alpha k^B)[\eta-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\phi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2}$  and  $0 < c < b$ ,  $\pi_{SW}^{B-c} > \pi_{SW}^I$ ; otherwise,  $\pi_{SW}^{B-c} \leq \pi_{SW}^I$ .

Proposition 5.2 shows that when the BCT variation cost is within a certain interval, comparing Model B-c and Model I, the launch success probability increases, the launch price increases, the retail price increases, and the insurance rate decreases. This result is the same as the outcomes in Proposition 4.1 (comparing Model B with Model I).

Moreover, by comparing the members' profits in Model B-c and Model I, we also find that when the marginal cost  $c$  under a threshold and the cost of BCT is low, all the members will benefit from adopting BCT.

Therefore, by comparing Model B-c and Model I in Proposition 5.2, our findings on the value of BCT are proved to be robust.

### 5.1.2. Model BG-c

Similar to Model BG, we build Model BG-c considering the marginal cost of BCT, which can be written as follows:

$$D^{BG-c} = 1 \int_{p^{BG-c-b}}^1 f(u) du = 1 - p^{BG-c} + b \quad (21)$$

Therefore, the members' payoffs can be measured as follows:

$$\begin{aligned}
\pi_S^{BG-c} &= e(p-c)D^{BG-c} - [\alpha + e(1-\alpha)]l - (r-g)(c_S + \alpha l) + (1-e)\beta(c_S + \alpha l) - c_S - c_{SB}, \\
\pi_I^{BG-c} &= r(c_S + \alpha l) - (1-e)\beta(c_S + \alpha l), \\
\pi_V^{BG-c} &= [\alpha + e(1-\alpha)]l - (1-e)\theta - (k^B e^2 + c_V) - c_{VB}, \\
s.t. \pi_V^{BG-c} &\geq 0.
\end{aligned} \tag{22}$$

Note, the only difference between Model BG-c and Model BG is that the BCT's marginal cost occurs to SO. We solve the derivation and summarize the outcomes in Table 16.

Table 16: The equilibrium outcomes in Model BG-c.

	$c_V < H(\alpha)$	$c_V \geq H(\alpha)$
Effort of VM exerting $e^*$	$\frac{\lambda-C}{16(1-\alpha)k^B}$	$\frac{\mu-\alpha k^B}{(1-\alpha)k^B}$
Launch price $l^*$	$l^* = l_S = \frac{\lambda-8\theta(1-\alpha)-C}{8(1-\alpha)^2}$	$l^* = l_{VA} = \frac{2\mu-2\alpha k^B-(1-\alpha)\theta}{(1-\alpha)^2}$
Retail price $p^*$	$\frac{1+b+c}{2}$	$\frac{1+b+c}{2}$
Premium rate $r^*$	$\beta(1 - \frac{\lambda-C}{16(1-\alpha)k^B})$	$\beta \frac{k^B-\mu}{(1-\alpha)k^B}$
SO's profit $\pi_S^{B-c}$	$\frac{\lambda^2-C(C-2\lambda)}{128(1-\alpha)^2k^B} + \frac{(1-g)\alpha\theta}{1-\alpha} - (1-g)c_S - c_{SB}$	$\frac{(\mu-\alpha k^B)(\phi+8\alpha k^B-8\mu-C)}{4(1-\alpha)^2k^B} + \frac{(1-g)\alpha\theta}{1-\alpha} - (1-g)c_S - c_{SB}$
VM's profit $\pi_V^{B-c}$	$\frac{\lambda^2+32\alpha k^B\lambda-C(C-2\lambda-32\alpha k^B)}{256(1-\alpha)^2k^B} - \frac{\theta}{1-\alpha} - c_V - c_{VB}$	0
Consumer surplus $CS^{B-c}$	$\frac{(1+b-c)^2}{8}$	$\frac{(1+b-c)^2}{8}$
Social welfare $SW^{B-c}$	$\frac{3\lambda^2+32\alpha k^B\lambda-C(3C-6\lambda-32\alpha k^B)}{256(1-\alpha)^2k^B} - \frac{\theta[1-(1-g)\alpha]}{1-\alpha} - (1-g)c_S - c_V - c_{SB} - c_{VB} + \frac{(1+b-c)^2}{8}$	$\frac{(\mu-\alpha k^B)(\phi+8\alpha k^B-8\mu-C)}{4(1-\alpha)^2k^B} + \frac{(1-g)\alpha\theta}{1-\alpha} - (1-g)c_S - c_{SB} + \frac{(1+b-c)^2}{8}$

To avoid complicated writing, we define  $\lambda = (1-\alpha)(1+b)^2 + 4(1-\alpha)\theta - 8\alpha k^B$ ,  $\mu = \sqrt{(1-\alpha)^2k^B(c_V + c_{VB}) + \alpha^2k^{B^2}} - (1-\alpha)k^B\theta$ ,  $C = (1-\alpha)c(2+2b-c)$ .

To explore the effect of blockchain marginal cost on the equilibrium outcomes under government subsidies, we compare model BG-c with Model BG and obtain Proposition 5.3.

**Proposition 5.3.** *Under Model BG-c, the satellite launch supply chain adopts the BCT with government-subsidies insurance considering the marginal cost of BCT.*

Compared with Model BG, (i) when  $c_V < H(\alpha)$ , (a)  $e^{BG-c} < e^{BG}$ ,  $l^{BG-c} < l^{BG}$ ,  $r^{BG-c} > r^{BG}$ ,  $p^{BG-c} > p^{BG}$ ; (b) if  $0 < c < 1+b - \sqrt{\frac{(1-\alpha)(1+b)^2-2\lambda}{1-\alpha}}$ ,  $\pi_S^{BG-c} > \pi_S^{BG}$ ; otherwise,  $\pi_S^{BG-c} \leq \pi_S^{BG}$ ; if  $0 < c < 1+b - \sqrt{\frac{(1-\alpha)(1+b)^2-2(\lambda+16\alpha k^B)}{1-\alpha}}$ ,  $\pi_V^{BG-c} > \pi_V^{BG}$ ; otherwise,  $\pi_V^{BG-c} \leq \pi_V^{BG}$ ;  $CS^{BG-c} < CS^{BG}$ ; if  $0 < c < 1+b - \sqrt{\frac{3(1-\alpha)(1+b)^2-6\lambda-32k^B}{3(1-\alpha)}}$ ,  $\pi_{SW}^{BG-c} > \pi_{SW}^{BG}$ ; otherwise,  $\pi_{SW}^{BG-c} \leq \pi_{SW}^{BG}$ ; (ii) when  $c_V \geq H(\alpha)$ ,

(a)  $e^{BG-c} = e^{BG}$ ,  $l^{BG-c} = l^{BG}$ ,  $r^{BG-c} = r^{BG}$ ,  $p^{BG-c} > p^{BG}$ ; (b)  $\pi_S^{BG-c} < \pi_S^{BG}$ ;  $\pi_V^{BG-c} = \pi_V^{BG} = 0$ ;  $CS^{BG-c} < CS^{BG}$ ;  $\pi_{SW}^{BG-c} < \pi_{SW}^{BG}$ .

Proposition 5.3 indicates the effect of marginal cost of BCT under government subsidies by comparing Model BG-c and Model BG, which is similar to.

Proposition 5.3 shows that the impact of BCT marginal cost under government subsidies derived by comparing model BG-c with model BG. It can be seen that the results are very similar to Proposition 5.1, the only difference being that the specific threshold of marginal cost becomes higher with government subsidies. That means the affordability of marginal costs is enhanced with the support of government subsidies.

Moreover, we compare Model BG-c with Model BG to explore whether the marginal cost changes the value of BCT under government subsidies, i.e., to verify the robustness of Proposition 4.3 and Proposition 4.4.

**Proposition 5.4.** *Under Model BG-c, the satellite launch supply chain adopts the BCT with government-subsidies insurance considering the marginal cost of BCT.*

Compared with Model IG, (i) when  $c_V < H(\alpha)$ , (a) if  $0 < c < 1 + b - \sqrt{\frac{(1+4\theta)k^B}{k} - 4\theta}$ ,  $e^{BG-c} > e^{IG}$ ,  $r^{BG-c} < r^{IG}$ ; otherwise,  $e^{BG-c} \leq e^{IG}$ ,  $r^{BG-c} \geq r^{IG}$ ; if  $0 < c < 1 + b - \sqrt{1 - \frac{8\alpha(1-g)(k-k^B)}{1-\alpha}}$ ,  $l^{BG-c} > l^{IG}$ ; otherwise,  $l^{BG-c} \leq l^{IG}$ ; if  $0 < c < b$ ,  $p^{BG-c} > p^{IG}$ , otherwise,  $p^{BG-c} \leq p^{IG}$  (b) if  $0 < c < 1 + b - \sqrt{\frac{(1-\alpha)(1+b)^2-2\lambda}{1-\alpha}}$  and  $c_{SB} < \frac{k\lambda^2-k^B\psi^2}{128kk^B(1-\alpha)^2}$ ,  $\pi_S^{BG-c} > \pi_S^{IG}$ ; otherwise,  $\pi_S^{BG-c} \leq \pi_S^{IG}$ ; if  $0 < c < 1 + b - \sqrt{\frac{(1-\alpha)(1+b)^2-2\lambda-32\alpha k^B}{1-\alpha}}$  and  $c_{VB} < \frac{k\lambda^2-k^B\psi^2+32\alpha k^B(\lambda-\psi)}{256kk^B(1-\alpha)^2}$ ,  $\pi_V^{BG-c} > \pi_V^{IG}$ ; otherwise,  $\pi_V^{BG-c} \leq \pi_V^{IG}$ ; if  $0 < c < b$ ,  $CS^{BG-c} > CS^{IG}$ ; otherwise,  $CS^{BG-c} \leq CS^{IG}$ ; if  $0 < c < 1 + b - \sqrt{\frac{3(1-\alpha)(1+b)^2-6\lambda-32\alpha k^B}{3(1-\alpha)}}$  and  $c_{SB} + c_{VB} < \frac{3k\lambda^2-3k^B\psi^2+32\alpha k^B(\lambda-\psi)}{256kk^B(1-\alpha)^2} + \frac{b^2+2b}{8}$ ,  $SW^{BG-c} > SW^{IG}$ ; otherwise,  $SW^{BG-c} \leq SW^{IG}$ .

(ii) when  $c_V \geq H(\alpha)$ , (a)  $e^{BG-c} > e^{IG}$ ,  $l^{BG-c} > l^{IG}$ ,  $r^{BG-c} < r^{IG}$ ; if  $0 < c < b$ ,  $p^{BG-c} > p^{IG}$ ; otherwise,  $p^{BG-c} \leq p^{IG}$ ; (b) if  $c_{SB} < \frac{k(\mu-\alpha k^B)[\lambda-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\psi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2}$ ,  $\pi_S^{BG-c} > \pi_S^{IG}$ ; otherwise,  $\pi_S^{BG-c} \leq \pi_S^{IG}$ ;  $\pi_V^{BG-c} = \pi_V^{IG} = 0$ ; if  $0 < c < b$ ,  $CS^{BG-c} > CS^{IG}$ ; otherwise,  $CS^{BG-c} \leq CS^{IG}$ ; if  $c_{SB} < \frac{k(\mu-\alpha k^B)[\eta-8(\mu-\alpha k^B)]-k^B(\omega-\alpha k)[\phi-8(\omega-\alpha k)]}{4kk^B(1-\alpha)^2}$  and  $0 < c < b$ ,  $\pi_{SW}^{BG-c} > \pi_{SW}^{IG}$ ; otherwise,  $\pi_{SW}^{BG-c} \leq \pi_{SW}^{IG}$ .

The results in Proposition 5.4 are similar to Proposition 5.2 that comparing Model BG-c and Model G, the launch success probability increases, the launch price increases, the retail price in-

creases, and the insurance rate decreases with the BCT variation cost in a certain interval. This result is the same as the outcomes in Proposition 4.3 (comparing Model BG with Model IG).

Besides, by comparing members' profits in Model BG-c and Model IG, we also find that when the marginal cost  $c$  under a threshold and the cost of BCT is low, all the members will benefit from adopting BCT under government subsidies.

Therefore, by comparing Model BG-c and Model IG, our findings in Proposition 4.3 and Proposition 4.4 about the value of BCT with the government subsidy are proved to be robust.

## 5.2. Alliance

Inspired by alliances in the real-world alliances, such as U.S. Space Enterprise Consortium and China Commercial Space Alliance, we extend the models to explore if an alliance strategy is a better to improve the effective of satellite launch supply chain in this section. On the basis of the main cases, we build three models: (i) the VM and SO form an alliance with launch insurance (Model IA); (ii) the VM and SO form an alliance with launch insurance under government subsidies (Model GA); (iii) the VM and SO form an alliance with blockchain-embedded launch insurance (Model BA); (iv) the VM and SO form an alliance with blockchain-embedded launch insurance under government subsidies (Model BGA).

In the above models, the VM and the SO attempt to maximize their respective benefits, VM by deciding the effort to be paid, and SO by determining the launch service price and retail price. However, in the alliance strategy, VM and SO will act as a whole alliance to decide the efforts exert and the retail price. Thus the market demand and payoff functions of Model IA can be written as follows:

$$D^{IA} = 1 - \int_{p^{IA}}^1 f(u) du = 1 - p^{IA} \quad (23)$$

$$\begin{aligned} \pi_{SC}^{IA} &= epD^{IA} - (1 - e)\theta - rc_S + (1 - e)\beta c_S - c_S - c_V, \\ \pi_I^{IA} &= rc_S - (1 - e)\beta c_S. \end{aligned} \quad (24)$$

The functions of Model GA, Model BA, and model BGA are similar to Model IA which we omit here. By inverse solving, we obtain the equilibrium outcomes which are summarized in Table 17 and Table 18

Table 17: The equilibrium outcomes in Model IA and Model GA.

	Model IA	Model GA
Effort of SC exerting $e^*$	$\frac{1+4\theta-4\beta c_S}{8k}$	$\frac{1+4\theta-4\beta c_S}{8k}$
Retail price $p^*$	$\frac{1}{2}$	$\frac{1}{2}$
Premium rate $r^*$	$\beta(1 - \frac{1+4\theta-4\beta c_S}{8k})$	$\beta(1 - \frac{1+4\theta-4\beta c_S}{8k})$
SC's profit $\pi_{SC}$	$\frac{(1+4\theta)^2-(4\beta c_S)^2}{64k} - \theta - c_S - c_V$	$\frac{(1+4\theta)^2-(4\beta c_S)^2}{64k} - \theta - (1-g)c_S - c_V$
Consumer surplus $CS$	$\frac{1}{8}$	$\frac{1}{8}$
Social welfare $SW$	$\frac{(1+4\theta)^2-(4\beta c_S)^2}{64k} - \theta - c_S - c_V + \frac{1}{8}$	$\frac{(1+4\theta)^2-(4\beta c_S)^2}{64k} - \theta - (1-g)c_S - c_V + \frac{1}{8}$

Table 18: The equilibrium outcomes in Model BA and Model BGA.

	Model BA	Model BGA
Effort of SC exerting $e^*$	$\frac{(1+b)^2+4\theta-4\beta c_S}{8k^B}$	$\frac{(1+b)^2+4\theta-4\beta c_S}{8k^B}$
Retail price $p^*$	$\frac{1+b}{2}$	$\frac{1+b}{2}$
Premium rate $r^*$	$\beta(1 - \frac{(1+b)^2+4\theta-4\beta c_S}{8k^B})$	$\beta(1 - \frac{(1+b)^2+4\theta-4\beta c_S}{8k^B})$
SC's profit $\pi_{SC}$	$\frac{[(1+b)^2+4\theta]^2-(4\beta c_S)^2}{64k^B} - \theta - c_S - c_V - c_{SB} - c_{VB}$	$\frac{[(1+b)^2+4\theta]^2-(4\beta c_S)^2}{64k^B} - \theta - (1-g)c_S - c_V - c_{SB} - c_{VB}$
Consumer surplus $CS$	$\frac{(1+b)^2}{8}$	$\frac{(1+b)^2}{8}$
Social welfare $SW$	$\frac{[(1+b)^2+4\theta]^2-(4\beta c_S)^2}{64k^B} - \theta - c_S - c_V - c_{SB} - c_{VB} + \frac{(1+b)^2}{8}$	$\frac{[(1+b)^2+4\theta]^2-(4\beta c_S)^2}{64k^B} - \theta - (1-g)c_S - c_V - c_{SB} - c_{VB} + \frac{(1+b)^2}{8}$



The outcomes above imply a difference that the optimal decisions are effected by the insurance market instead of the prepay rule. That means, as the VM and SO form an alliance, the motivation of VM to improve the successful launch probability changes from the prepay ratio ( $\alpha$ ) to the insurance claim ( $\beta c_S$ ). Thus, the less insurance covers, the more effort VM exerts. By comparing Model IA and Model I, model GA and Model IG, Model BA and Model B, Model BGA and Model BG, we get Proposition 5.5.

**Proposition 5.5.** *When the VM and the SO form an alliance,*

- (i) *comparing Model IA and Model I, if  $\beta c_S < \frac{(1-\alpha)(1+4\theta)+8\alpha k}{8(1-\alpha)}$ , then  $e^{IA} > e^I$  and  $SW^{IA} > SW^I$ ;*
- (ii) *comparing Model GA and Model G, if  $\beta c_S < \frac{(1-\alpha)(1+4\theta)+8\alpha k(1-g)}{8(1-\alpha)}$ , then  $e^{GA} > e^{IG}$ ; if  $(\beta c_S)^2 < \frac{[(1-\alpha)(1+4\theta)+8\alpha k(1-g)]^2+32\alpha k g[(4\theta-1)(1-\alpha)+8\alpha k(1-g)]}{[8(1-\alpha)]^2}$ , then  $SW^{GA} > SW^{IG}$ ;*
- (iii) *comparing Model BA and Model B, if  $\beta c_S < \frac{(1-\alpha)[(1+b)^2+4\theta]+8\alpha k^B}{8(1-\alpha)}$ ,  $e^{BA} > e^B$  and  $SW^{BA} > SW^B$ ;*
- (iv) *comparing Model BGA and Model BG, if  $\beta c_S < \frac{(1-\alpha)[(1+b)^2+4\theta]+8\alpha k^B(1-g)}{8(1-\alpha)}$ ,  $e^{BGA} > e^{BG}$ ; if  $(\beta c_S)^2 < \frac{\{(1-\alpha)[(1+b)^2+4\theta]+8\alpha k^B(1-g)\}^2+32\alpha k^B g\{[4\theta-(1+b)^2](1-\alpha)+8\alpha k^B(1-g)\}}{[8(1-\alpha)]^2}$ ,  $SW^{BGA} > SW^{BG}$ .*

Proposition 5.5 gives the specific insurance claim thresholds for the adoption of the alliance strategy under four scenarios. Note that the retail price paid by the consumer and the consumer surplus remain the same, so the increased social welfare mainly comes from the increase in supply chain profits.

Therefore, when the insurance market is soft, it would be a wise idea to pursue an alliance strategy in the satellite launch supply chain. It will contribute to an increase in the probability of successful launches as well as to the improvement of social welfare.

## 6. Conclusions

### 6.1. Remarkable findings

Nowadays, with the prosperity of commercial launches, more and more research is being conducted in the operation management of space. Motivated by the real-world government-subsidized launch insurance project, we explored the operations of the satellite launch supply chain with

government-subsidized insurance. Firstly, we established the traditional insurance model (Model I) and the government-subsidized insurance model (Model IG). By deriving analytical results, we demonstrate the optimal decisions for each participant. We have further uncovered the effect of the subsidies on different variables. Finally, we built value models to investigate the benefit of subsidies, especially revealing the conditions under which one model outperforms the other.

However, we find that if only the government provides subsidies, the customers cannot benefit. So we investigate the blockchain applications in the space launch supply chain by building a blockchain-embedded insurance model (Model B), which has also been implemented in the real world. Besides, considering the high blockchain costs, we explored the scenario of adopting blockchain under government subsidies (Model BG). At last, in order to measure the value of blockchain under different scenarios, we compare Model B with Model I and Model BG with Model IG. And we analyzed the change of blockchain impact under the government subsidy scenario.

As a concluding remark, we highlight the answers as follows:

- (1) Government subsidized launch insurance can achieve win-win in satellite launch supply chain and improve the social welfare. However, it is not always preferred to implement the government subsidy in all cases. When the government provides subsidies, it is necessary to screen satellite vendors, and only by subsidizing satellite launch activities with inexpensive vehicles can it effectively promote the development of the launch market. Otherwise, subsidies can only increase the profit of satellite operators but can not promote the launch success rate, which is not conducive to the optimal allocation of government funds.
- (2) The government subsidies have helped to establish positive feedback for the satellite launch market; that is, the satellite vendor is more willing to pay high launch price, so that the vehicle manufacturer is motivated to increase the probability of successful launches.
- (3) Once the government subsidy project is launched, the satellite operator will always get more from it than before. But for the vehicle manufacturer, only when the cost of vehicle is relatively low, his income will increase compared to before; otherwise, he cannot benefit from the subsidy program. For consumers, there is no change in consumer surplus. Therefore, the

overall social welfare as the sum of the profit of the various subjects will increase.

- (4) In the blockchain-embedded model, the values that blockchain bring to the optimal decisions are similar to the government subsidy brings. However, there is one difference to claim that the retail price has been increased and the market demand also increases.
- (5) Moreover, for the satellite, she will always benefit from the adoption of blockchain if its cost is relatively low.
- (6) However, the profitable condition for the vehicle to decide whether use the blockchain is not only the cost of blockchain is expensive but also the cost of vehicle manufacturing is low.
- (7) Significantly, the use of the blockchain launch platform will make the consumer surplus increase no matter in which situation.
- (8) Interestingly, the adoption of blockchain can increase the benefits of government subsidies. Besides, when the supply chain obtains the government subsidies, both the satellite operator and the vehicle manufacture can enhance the affordability of blockchain costs.

## *6.2. Managerial implications*

Analyzing the derived findings, we further propose the following managerial implications, which help form action plans for satellite operators, vehicle manufacturers, and the government.

**Satellite operator:** It is the most effective to improve profit by applying for government insurance subsidies. Moreover, the adoption of the blockchain-embedded launch platform will also enhance the profit when the cost of blockchain is low.

**Vehicle manufacturer:** Only when vehicle costs are low can manufacturers indirectly enjoy the benefits of government subsidies. Otherwise, the manufacturer will be nonprofitable. However, it is worth noting that adopting blockchain technology to provide launch services is always beneficial for vehicle manufacturers, as it can increase the probability of a successful launch. Besides, when the blockchain and vehicle manufacturing costs are low, adopting blockchain technology is the best strategy for the manufacturer, which will improve his profitability.

**Government:** Intuitively, government provision of insurance subsidies can improve social welfare. However, the excellent way to optimally allocate the limited subsidy funds is to disburse the subsidies to satellite operators who choose cost-effective vehicles. This is because it is in this

condition that the probability of a successful launch is increased, and a virtuous closed-loop commercial satellite launch market is promoted. Finally, this results in a win-win situation in the supply chain. However, it is worth noting that when the government provides subsidies to blockchain technology embedded launch activities, it will maximize the funds' effectiveness, achieving all-win among the satellite operator, the vehicle manufacturer, and customers.

### 6.3. Future research

For the future studies, we suggest several probable future directions. First, the risk attitude of different participants can be taken into account which will effect the optimal decisions. Second, the JIT operation management with the supported of blockchain in launch supply chain can be promising directions for future research. Last but not least, multi-tier supply chain or supply chain network will be interesting to investigate, which involve more members such as the rideshare broker in piggyback launch and rideshare or cluster launch (Barschke, 2020).

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